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ECONOMIC ANALYSIS OF THE PROCESSING AND DISPOSAL OF REFUSE SLUDGES

CURRAN ASSOCIATES, INCORPORATED

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16. ABSTRACT

This is the second in a series of technical reports evaluating the economic and technical feasibility of wet systems for residential refuse collection. The major focus of this report is the economic and technical feasibility of sludge handling and disposal at wastewater treatment facilities modified to accept up to 0.5 percent by weight of ground residential refuse in their sewage influents. Using computer simulation techniques, the sensitivity of sludge handling and disposal operations to operating parameters and input conditions is examined. A substantial decrease in the unit cost of sludge handling (on a per ton of dry solids basis) over plants treating sewage alone can be expected, and suitable process chains include gravity thickening, vacuum filtration and either landfill or incineration. Energy recovery by way of anaerobic digestion is also considered.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multi-disciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described here presents an investigation to determine the feasibility of hydraulic transport of ground refuse in sanitary sewers of conventional design.

This report is one of several final reports examining the technical and economic feasibility of collecting and transporting residential solid wastes via an underground, wet pipeline (sewer) system. The research was aimed at improving the overall management and reuse of solid waste to the benefit of both the individual citizen and the national environmental picture. All possible aspects of this new concept were considered including the physical, mechanical, chemical, and socio-economic, and the environmental. It is the conclusion of the study that the wet system concept is extremely feasible technically, socially, and environmentally; but that the system's economics do not appear too reasonable at this time except for specialized applications.

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The responsibility for the accuracy and opinions expressed in this report, however, remains solely that of the writers.

SUMMARY OF CONCLUSIONS

The major conclusions of this study can be summarized as follows:

1. The cost of dewatering and disposal of the sludge generated at a sewage treatment facility handling ground refuse is estimated to be in the range of $15 to $25 per ton of dry solids, and substantially below that of a treatment facility handling only sewage solids. The major determinants of total per ton cost are per capita refuse generation rates and the number of persons served by the facility.

2. Economies of scale and the predominance of a more readily dewaterable primary sludge are the major reasons for the relatively low unit costs. The sludge handling facilities of a secondary plant handling an average residential refuse generate rate correspond to the size of the facilities handling only primary sewage sludge generated by 9 to 12 times the number of inhabitants.

3. Because of the much higher ratio of primary to secondary sludge at a facility treating ground refuse, separate treatment chains for the primary and secondary sludges are not recommended. The small amount of secondary sludge, when mixed with the primary sludge will have little or no impact on the thickening and dewatering characteristics of the primary sludge that would be rich in refuse solids.

4. The most promising sludge handling process chain includes thickening, vacuum filtration and disposal by landfill. Anaerobic digestion prior to vacuum filtration would be economic if the market price of methane were to exceed about $0.80 per 1000 cu. ft., and incineration should also be considered if landfill conditions are unfavorable. Advanced technologies, such as pyrolysis, were not investigated due to lack of appropriate data.

CHAPTER I

INTRODUCTION

This report is the second of four reports prepared by Curran Associates under Contract 68-03-0183 from the EPA Solid Waste Research Laboratory to study the technical and economic feasibility of Wet Systems for Residential Refuse Collection.[1] The first report undertook a preliminary assessment of economic and technical feasibility of the concept with a view to establishing the order of magnitude of costs involved, and to identify the major areas of technical uncertainty.[2] One of the conclusions of this preliminary phase was that the economic feasibility of the entire concept was closely related to the cost of sludge handling. This second study therefore addresses this question of sludge costs in some detail, albeit cognizant of the difficulties of realistic cost estimation in the absence of any significant body of experience or even laboratory data on the physical-chemical characterization of the sludges that might be produced at treatment facilities handling ground refuse in sewage.

A third report undertakes a detailed case study with the objective of developing specific conclusions and cost estimates for the conditions encountered in an area typical of the Nation's urbanized regions.[3] And finally, the fourth report of the series documents the computer program developed for the assessment of treatment costs.[4]

Wet Systems for Residential Refuse Collection

The wet systems concept embodies grinding residential refuse in appliance-like grinders in the individual home, then conveying the slurry through the existing sewer system to a modified wastewater treatment facility where it would be processed. The nature of the treatment plant influent would obviously be different from that encountered today, and many changes would be necessary at existing facilities to maintain adequate treatment. The indications are, however, that the major impact would occur in preliminary and primary treatment, and in the subsequent sludge handling operations. This study is therefore addressed to the problems of sludge processing and disposal at a sewage treatment facility whose influent may contain between 1/4 to 1/2 percent by weight of ground refuse.

To the extent that glass and ceramics are transportable in the sewer system, the grit quantities at the treatment facility would increase substantially. However, this increase could probably be adequately removed in appropriately designed conventional grit chambers.[5] The suspended solids would increase also with the addition of ground refuse, but appear to be adequately settleable for removal in conventional settling basins.[6] Organic loads to secondary treatment units would be somewhat higher than are encountered normally, but probably would not

be much more than are encountered today at facilities which serve areas with a high percentage of garbage grinders. The amount of floating matter encountered in the settling basins would increase substantially, and modifications to skimming devices might be necessary. This floating matter would result from the introduction of significant amounts of cellophane, plastics, and garden waste normally found in residential refuse.

A more detailed description of the wet systems concept is to be found in the report containing the preliminary assessment,[7] and in particular Chapter IV, describing the impact of the concept on treatment facilities as a whole, and secondary and advanced treatment in particular, is pertinent to this report.

Objectives of the Study

This study should be interpreted as a preliminary effort to analyze a very complex problem, and will need to be extended considerably before even a pilot scale demonstration facility is contemplated. The major constraint limiting both the scope of this study and its accuracy is the exceptionally limited experimental evidence available to us at the present time. However, we are confident that our predictions of total costs are entirely adequate for the primary purpose of the contract which is to establish the order of magnitude of cost for the wet systems concept as a whole, even if we have not been able to address the myriad of operational complexities in sufficient detail to make definitive judgments on process selection and operation.

Perhaps the most important specific goal of this study is to establish the unit cost of sludge handling when ground refuse is added to the treatment plant input. The cost of collection and disposal of residential refuse under existing management concepts lies in the range of $20 to $60 per ton; consequently, if the cost of just the sludge handling in a wet system is also $20 to $60 per ton (of dry solids), as would be expected on the basis of existing practice at sewage treatment plants, then the economic feasibility of the wet systems concept is questionable, even given that the transformation of solid waste to sludge solids is not 1 to 1.

Plan of Study

We turn next, in Chapter II, to an analysis of the quantity and quality of the sludge that would likely be generated at a treatment facility handling ground refuse. Despite the shortcomings of the available data, several important inferences crucial to the selection of suitable process configuration may nevertheless be made. Chapter III describes the mathematical models and the cost functions to be utilized for each unit operation.

Computerized versions of these models were linked together and subjected to a series of simulations designed to evaluate optimal process configurations, the trade-offs between individual unit operations, and the optimal values of operating parameters and total system costs. In order to keep the simulations within reasonable limits, four alternative process combinations were selected in advance, and the results of these simulations are discussed in Chapter IV. Because of its length, a computer program listing is not included in this report, but it may be obtained from the contractor on request. Finally, the conclusions of the study are summarized in Chapter V.

CHAPTER II

ANALYSIS OF SLUDGE QUANTITY AND QUALITY

Introduction

There is critical lack of information on the physical-chemical characterization and treatability of ground refuse in sewage, knowledge that is most important to an estimation of sludge quantities and quality. The only comprehensive study is that of Metcalf and Eddy,[8] conducted as part of the initial Foster-Miller investigation,[9] and some information is also available from experiments conducted in the early 1960's in Los Angeles.[10] A similar situation appears in the case of information on the physical-chemical characterization of sludges resulting from the treatment of ground refuse in sewage; apart from the very limited dewatering experiments conducted by Metcalf and Eddy, only a few studies whose focus was energy production from solid waste by anaerobic digestion appear to contain pertinent information. The studies by Pfeffer[11,12] are the most useful in this respect. Other information was also available from researchers attending a National Science Foundation State-of-the Art Conference on the conversion of solid waste to energy held at the University of Massachusetts in June 1973.[13]

Sludge Quantities

The major factor affecting the quantity of sludge produced at a treatment facility handling ground refuse is the per capita refuse generation rate. Other factors to be considered include sedimentation efficiency, the conversion of dissolved organic matter to settleable biomass and the per capita generation of sewage solids.

Influent Suspended Solids Concentrations. Metcalf and Eddy experienced considerable difficulty in making suspended solids determinations of unsettled ground refuse-sewage mixtures,[14] and the reports on the Los Angeles experiments contained no quantitative information on this subject. However, one can obtain some rough estimates by a solids balance, as shown on Figure 1. A typical daily per capita refuse generation of 2.25 lbs (1.02 kg) may result in 1.575 lbs (0.715 kg) of dry solids ground and entering the sewers per capita per day. Of this, about 0.17 lb (0.077 kg) will typically be grit, and from the Metcalf and Eddy measurements of dissolved solids in the supernatant of the settling tests, one obtains 0.005 lb (0.0022 kg) of dissolved solids per capita per day. Consequently, 1.4 lbs/cap/day (0.635 kg/cap/day) will be in the form of suspended solids. This converts to an additional 1678, 2238, and 3357 mg/ℓ at 100, 75, and 50 gals/cap/day (378.5, 284 and 189 ℓ/cap/day) of sewage at the treatment plant inflow, respectively. In contrast, the concentration of suspended solids in sewage treatment plant influents is usually in the range of 100 to 350 mg/ℓ, depending upon per capita suspended solids loading and upon

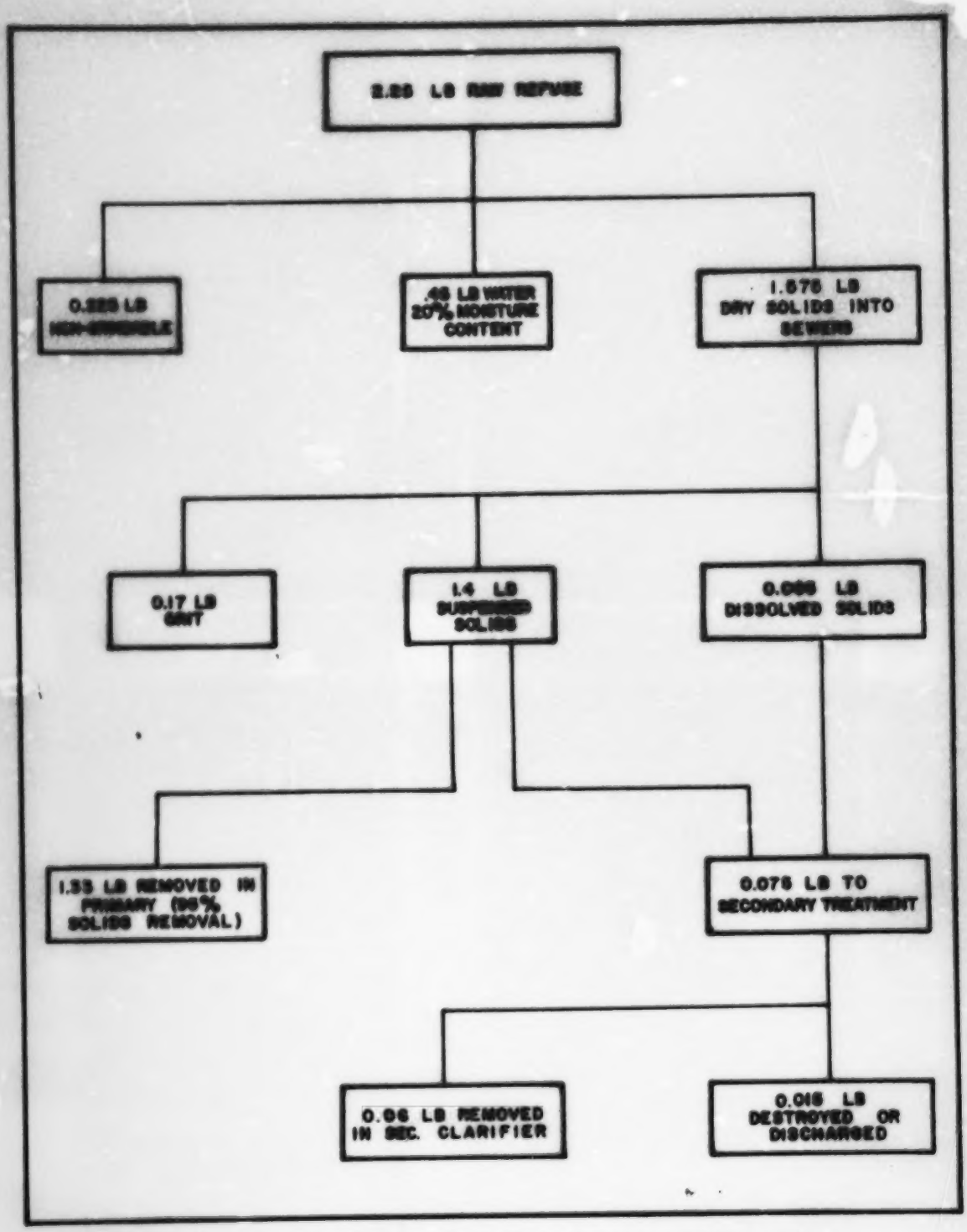

Figure 1: Mass Balance for Refuse Solids, lb per capita per day
(Source: Meier, Kühner & Martel, op. cit., Figure 12)

such factors as infiltration or the presence of industrial waste.

Primary Sludge Production. Average suspended solids loadings encountered at conventional sewage treatment plants lie in the range of .15 to .25 lb/cap/day, of which typically 60 percent may be removed in primary treatment. Of the additional suspended solids loading due to the addition of ground refuse, Whitney concluded on the basis of the Los Angeles experiments that primary settling would remove 95 percent. Using the suspended solids concentration in the influent calculated previously, the effluent from the primary settler would contain an additional 84, 112, or 168 ppm of suspended solids at 100, 75, and 50 gal/cap/day (378.5, 284, and 189 ℓ/cap/day), respectively, due to the addition of ground refuse. Then the daily per capita dry solids removed in primary settling, denoted σ_p, is given by:

$$\sigma_p = 0.95 \left[\frac{1.4}{2.25} \text{REF} + 0.6 \, SS_s \right] \qquad [1]$$

where REF is the lbs of total raw refuse generated per capita per day, and SS_s is the lbs of suspended solids in sewage per capita per day. This formulation assumes that the removal of sewage solids is unaffected by the presence of refuse solids. This may indeed be somewhat questionable, but in the absence of any data, probably more reasonable than other assumptions.

For the evaluation of the solids concentration in the primary sludge after settling of the ground refuse-sewage suspension, we have only the experimental results of Metcalf and Eddy. Their settling tests resulted in a sludge of about 5 percent solids content, which corresponds to that observed at many existing treatment plants.[15]

Waste Activated Sludge Production. With respect to secondary sludge production in the presence of ground refuse, knowledge of likely BOD inputs to the activated sludge units is necessary. Metcalf & Eddy found that the BOD in the supernatant after one hour of settling could be expressed by the equation:[16]

$$y(C) = y(0) + 143.3 \, C \qquad [2]$$

where C is the percentage of ground refuse in sewage by weight, y(C) is the BOD in mg/ℓ at that concentration C, and y(0) is the BOD in mg/ℓ with no refuse added.

McCarty and Broderson[17] have estimated that for every pound of BOD entering a conventional activated sludge process, 0.65 pounds (0.3 kg) of active solids are produced. Of these, 81.5 percent are destroyed by endogenous respiration to give carbon dioxide and water, and the remainder can be assumed to yield sludge solids. Thus, one pound of BOD will yield 0.12 pounds (0.054 kg) of sludge solids, and the total daily per capita production of waste activated sludge solids, denoted σ_s, is given by:

$$\sigma_s = (0.12\beta + 0.05 \frac{1.4}{2.25} \text{REF} + 0.4\ SS_s)\eta_s \qquad [3]$$

where η_s is the efficiency of the secondary clarifier, and β is the per capita BOD loading in the primary effluent. This assumes that the degradation of that portion of the BOD contributed by the refuse has the same kinetics as that of the domestic sewage, an assumption that is consistent with the Metcalf & Eddy tests. It also assumes that there is no degradation of solids carried over from the primary settler, a conservative assumption that would tend to overestimate sludge handling costs.

Estimates of Sludge Quantities. Using Equations 1 and 3, the daily dry solids quantities of primary and waste activated sludge were computed as a function of refuse generation rate, with the results shown on Table 1. Also shown is the daily estimated volume assuming a solids concentration of 5 percent in the primary sludge and 1 percent in the secondary. In the case of an average raw refuse generation rate of 2.25 lb/cap/day (1.02 kg/cap/day), the addition of ground refuse to the sewage will result in about a fifteen fold increase in the quantity of primary sludge. On the other hand, because of a very small increase in the BOD in the primary settler effluent due to the ground refuse, the volume and dry solids content of the waste activated sludge will change much less. Under the same condition (2.25 lb/cap/day of raw refuse) there will be only a 45 percent increase of the quantity of waste-activated sludge, which is still in the range of variation exhibited by existing sewage treatment plants. The quantity and the concentration of the mixture of primary and waste activated sludge are therefore affected primarily by variations in the primary sludge.

The amount of dry solids of the sludge mixture of primary and waste activated sludge (subsequently referred to as sludge) in tons per year, and the quantity of sludge in mgd, as a function of population and refuse generation rate, appear in Figures 2 and 3, respectively.

In order to dramatize the impact of the ground refuse upon the sludge handling, quantity-concentration flow diagrams of a conventional sewage treatment plant and a sewage treatment plant handling ground refuse in addition to sewage were plotted. Assuming a sewage generation rate of 100 gal/cap/day (378.5 ℓ/cap/day), Figure 4 shows the consequent flows (in the percentages of the incoming sewage) and their concentrations. Similarly, Figure 5 shows the flow diagram of a treatment plant handling 100 gal/cap/day of sewage plus 2.25 lb/cap/day of ground refuse.

Comparison of these diagrams reveals the magnitude of the impact of ground refuse additions. For example, the volumetric flow rate of vacuum filter cake shows an increase from 0.04 to 0.34 percent of the influent volume. This implies that at a 10 mgd (37,850 cu.m/day) facility, the filter cake would increase from 4,000 to 34,000 gal/day

Table 1: Daily Quantities of Sludges

RAW REFUSE GENERATION RATE	PRIMARY SLUDGE		WASTE ACTIVATED SLUDGE		MIXTURE OF PRIMARY AND WASTE ACTIVATED SLUDGES			RATIO OF PRIMARY TO WASTE ACTIVATED SLUDGES*
	VOLUME @ C=5%	DRY SOLIDS	VOLUME @ C=1%	DRY SOLIDS	VOLUME	CONCENTRATION	DRY SOLIDS	
lb/cap/day	gal./1000 pop.	lbs./1000 pop.	gal./1000 pop.	lbs./1000 pop.	gal./1000 pop.	%	lbs./1000 pop.	
sewage only	220	91.7	890	74.2	1110	1.8	165.9	1.2
0.5	920	383.6	1010	84.2	1930	2.9	447.8	4.6
1.0	1630	679.7	1140	95.1	2770	3.4	774.8	7.1
1.5	2340	975.8	1260	105.1	3600	3.6	1080.9	9.3
2.0	3050	1271.8	1380	115.1	4430	3.8	1386.9	11.0
2.25	3410	1422.0	1440	120.1	4850	3.8	1542.1	11.9
2.50	3760	1567.9	1500	125.1	5260	3.9	1693..	12.5
3.00	4470	1864.0	1630	135.9	6100	3.9	1999.9	13.7
3.50	5180	2160.1	1750	146.0	6930	4.0	2306.1	14.8
4.00	5890	2456.1	1870	156.0	7760	4.0	2612.1	15.7
4.50	6590	2748.0	1990	166.0	8580	4.0	2914.0	16.6

*On a dry solids basis.

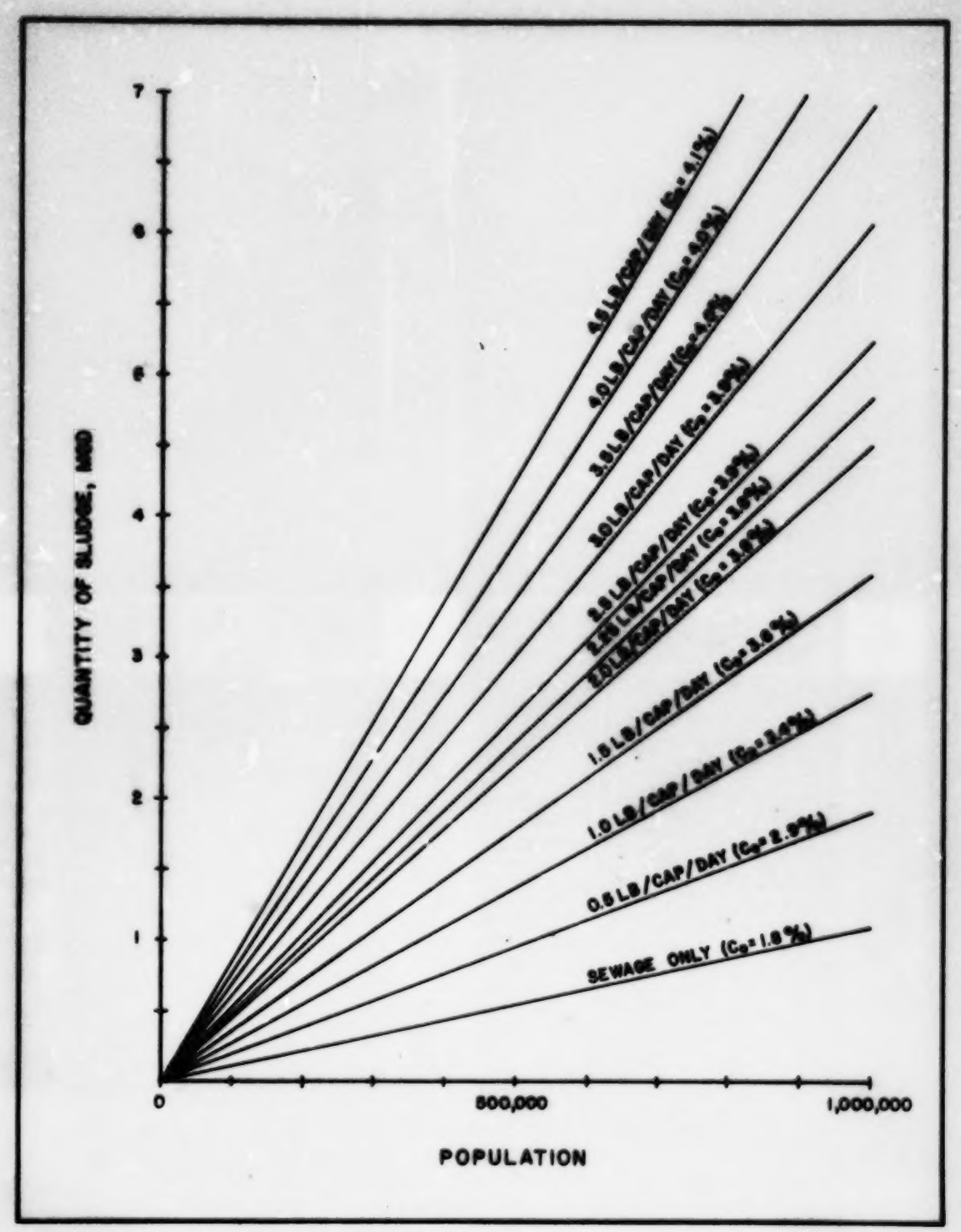

Figure 2: Dry Sludge Solids as a Function of Population and Refuse Generation

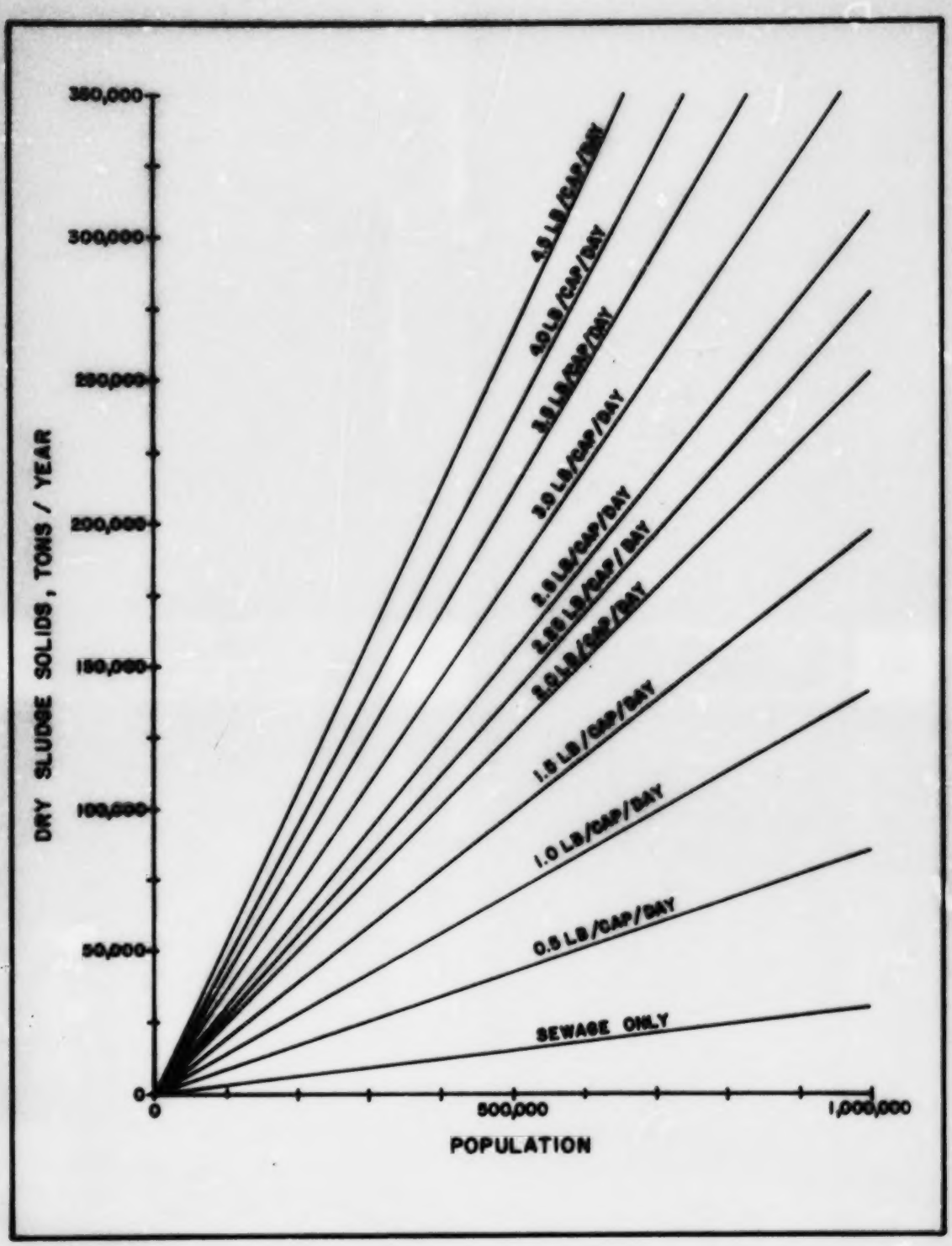

Figure 3: Quantity of Sludge as a Function of Population and Refuse Generation

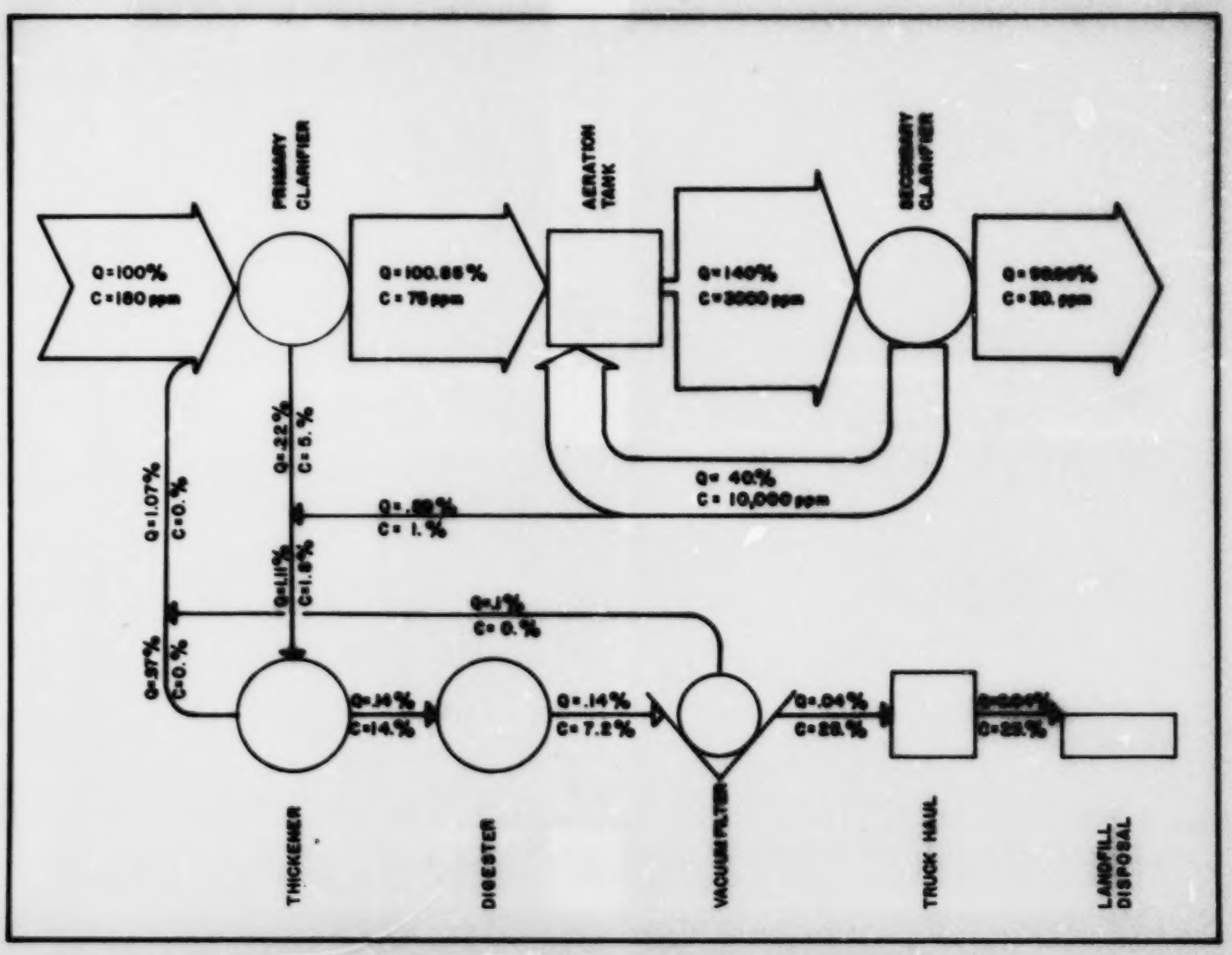

Figure 4: Flow Diagram of Sewage Treatment Plant Handling 100 gal/cap/day

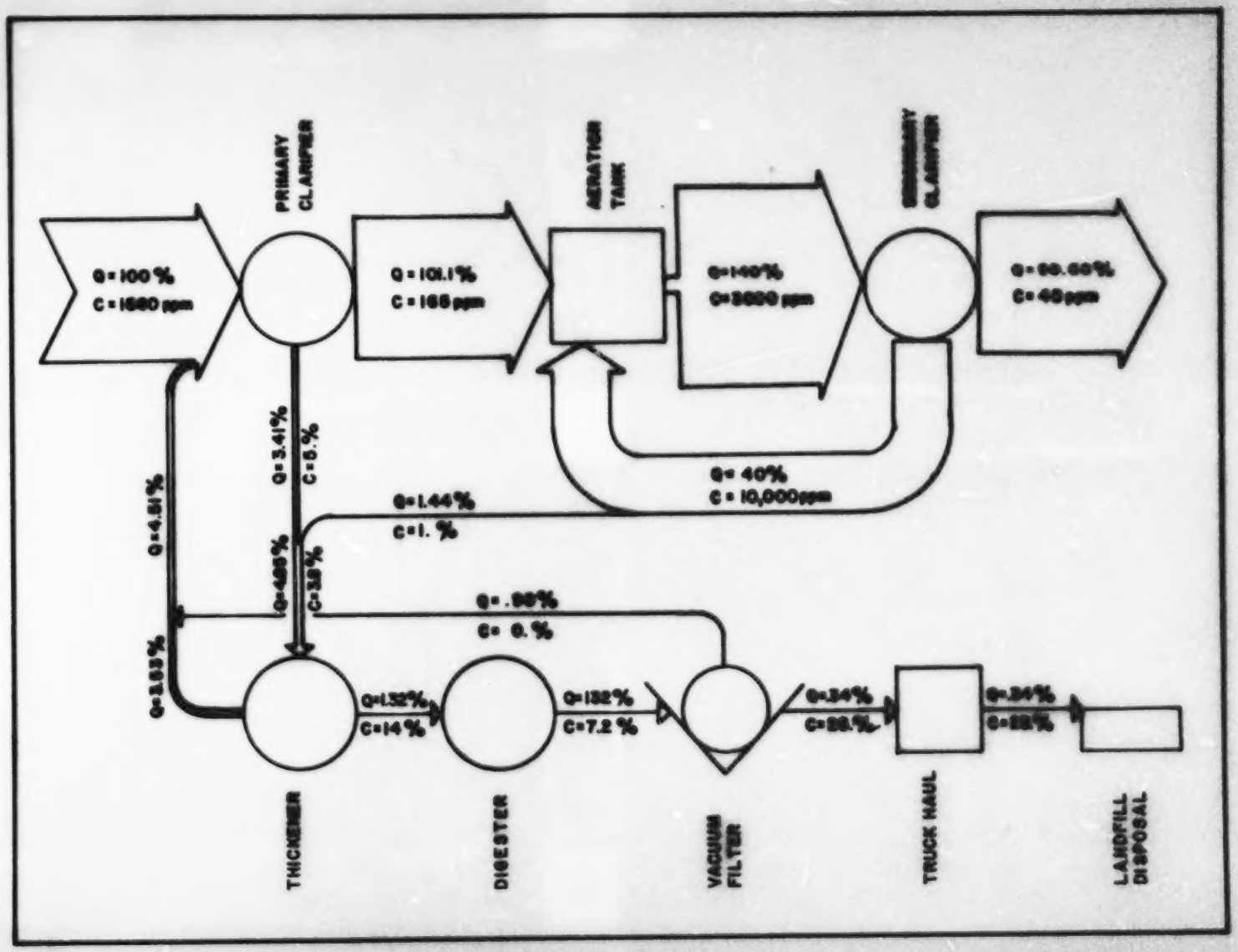

Figure 5: Flow Diagram of Sewage Treatment Plant Handling 100 gal/cap/day plus 2.25 lb/cap/day

(15,140 to 128,690 ℓ/day). For the total raw refuse generation rates of 1.0, 2.25, or 4.5 lb/cap/day (0.454, 1.02, or 2.04 kg/cap/day), a 2.5, 4.3 and 7.8-fold increase of sludge quantities must be expected. Using a dry solids basis (which is unaffected by concentration variations of the sludge) rather than a volumetric measure, the introduction of ground refuse into the sewage under the same conditions as above will result in the 4.7, 9.3 and 17.5-fold increase of dry sludge solids, respectively. Note that the difference between the volumetric and dry solids increases are due to the increase in concentration of the primary-secondary mixture. In summary, the sludge handling facilities of a sewage treatment plant handling an average 2.25 lb/cap/day (1.02 kg/cap/day) of ground refuse will correspond to a conventional treatment plant handling a population that is approximately nine times larger.

Sludge Quality

As noted previously, information on the quality parameters of ground refuse sludges is very limited, consisting of the Metcalf & Eddy studies and isolated information from a few studies whose focus was energy production from solid waste. In particular, there appear to be no measurements of quantitative sludge parameters such as coefficient of compressibility or specific resistance, both of obvious importance to assessments of dewatering characteristics. This is an area that is in urgent need of more detailed investigation if the wet systems concept is to be further pursued.

Raw Sludge. Metcalf & Eddy[18] found that 1-hour settling of ground refuse in sewage produced a sludge of about 5 percent solids content. Much of the suspended solids, consisting mainly of paper products, did not settle, or only very slowly. However, the dewatering characteristics of this primary sludge (including the floatables) appeared to be good. Metcalf & Eddy tested three devices for dewatering the primary sludge produced by adding ground refuse to sewage, although tap water rather than sewage was used in these laboratory tests: a Smith and Loveless sludge concentrator, a Komline-Sanderson vacuum filter, and a Bird centrifuge. All three devices worked well, and neither the vacuum filter nor the centrifuge required addition of chemicals. For all three methods tested, they obtained a sludge cake of at least 25 percent solids content. The yield of a vacuum filter was at least 8 pounds per square foot per hour (39.06 kgs/sq.m/hr), and Metcalf and Eddy judged that it could serve as the only dewatering unit.

The specific resistance and coefficient of compressibility of sludge are quantitative measures of its dewatering characteristics, but unfortunately Metcalf & Eddy did not evaluate them, and these are as yet unknown for the sludges obtained when ground refuse is added to sewage. The vacuum filtration yield reported by Metcalf & Eddy is in

the range of expected yields of chemically conditioned primary sludge, and therefore the dewatering characteristics of primary sludge of a sewage treatment plant handling ground refuse will be considered to be the same as those of chemically conditioned primary sludges. This assumption is not unreasonable in the light of some recent experiments at the University of Texas by Carden and Malina[19] on the efficacy of pulped newsprint as a sludge conditioner. Pulp additions of about 100 to 125 percent of the weight of sludge solids were found to reduce the specific resistance of activated sludge to levels comparable to the optimal levels attained with ferric chloride or cationic polymers. It was noted that the conditioning effect of the newspaper pulp increased as the solids content of the activated sludge increased, and it was concluded that the chemical conditioners could be replaced by the paper pulp with essentially similar results. This means that we might expect paper fiber in the primary sludge to act as a conditioner for the activated sludge fraction.

There is no information on the thickening of the sludge that would be generated in a sewage treatment plant handling refuse. On the basis of the apparent similarity between filtration characteristics of the primary sludge at sewage treatment plants handling ground refuse and ordinary chemically conditioned primary sludge the thickening of these two kinds of sludges may also be assumed to be similar.

The remaining problem is the effect of adding a small portion of secondary treatment sludge upon the character of primary sludge. It is usually reported that the specific resistance or vacuum filter yield is less than for the mixture of primary and activated sludges than for primary sludge alone. On the basis of the laboratory thickening experiments, Konicek, Kos, and Pardus[20] found, however, that the addition of activated sludge to primary sludge in the ratio occurring in a conventional secondary treatment plant had little significant effect on the thickening of primary sludge.

In light of these facts and because of the very high ratio of primary to waste activated sludge at the treatment plant handling refuse, the addition of waste activated sludge to the primary sludge will most likely have little or no effect upon the thickening and filtration characteristics of the primary sludge. Consequently, the characteristics observed for primary sludge by Metcalf & Eddy may be assumed to hold also for the primary-secondary mixture.

Digested Sludge. Pfeffer, who used the filter-leaf technique, found that the residue from digestion of refuse-sewage sludge dewatered very easily, without addition of conditioners.[21] This is in contradiction to the findings of Wise,[22] who found that the digester residue dewatered only with difficulty. However, the reactor solids concentrations used by Wise were below 2 percent, whereas Pfeffer's were generally above 6 percent. In the absence of a comprehensive study of the residue after digestion of refuse-sewage sludges, we must assume

that the quality of the digested refuse-sewage sludges will be the same as that of the ordinary digested sludge. Although it is recognized that this assumption is subject to question, it is unavoidable in the absence of any actual data. But insofar as this assumption does imply a need for chemical conditioner additions prior to dewatering, it is probably conservative.

CHAPTER III

UNIT OPERATIONS

Introduction

This chapter considers the mathematical models of each of the unit operations that were developed for the simulation program. The relationships between these individual unit operations are addressed in Chapter IV in the context of the specific process combinations considered. Most of the cost functions built into the individual unit operation models are taken from the recent study conducted for EPA by Black and Veatch,[23] whereas the design relationships have been taken from a variety of published sources or derived by the writers. But only in the latter cases are details of the underlying assumptions or theories fully elaborated.

Gravity Thickening

In the total absence of experimental data on gravity thickening of refuse-sewage sludges, the conventional methods of thickener design, based on plots of underflow concentration, depth of thickening zone and surface solids loading, were not considered applicable. Instead, we have utilized an empirical relationship developed by Eckenfelder, namely[24]

$$\frac{C_u}{C_f} - 1 = \frac{k}{G^n} \qquad [4]$$

where: C_u = underflow concentration (= conc. of thickened sludge), percent solids

C_f = feed solids concentration, percent solids

G = surface solids loading, $lb/ft^2/day$

k, n = constants

Given the feed solids concentration, then G, and hence the surface area of the thickeners, is a simple function of the underflow concentration. Based upon the experimental results of gravity thickening by Konicek, Kos and Pardus,[25] the values of the constants were set at n=0.5 and k=5.5. Under these assumptions, and for a feed solids concentration of 4 percent, the relationship between the surface solids loading of the gravity thickener and solids concentration of thickened sludge is as shown on Figure 6.

Cost Functions. The cost functions for thickening were taken from Patterson and Banker,[26] wherein the capital costs as well as manpower requirements and material and supply costs are given as a function of

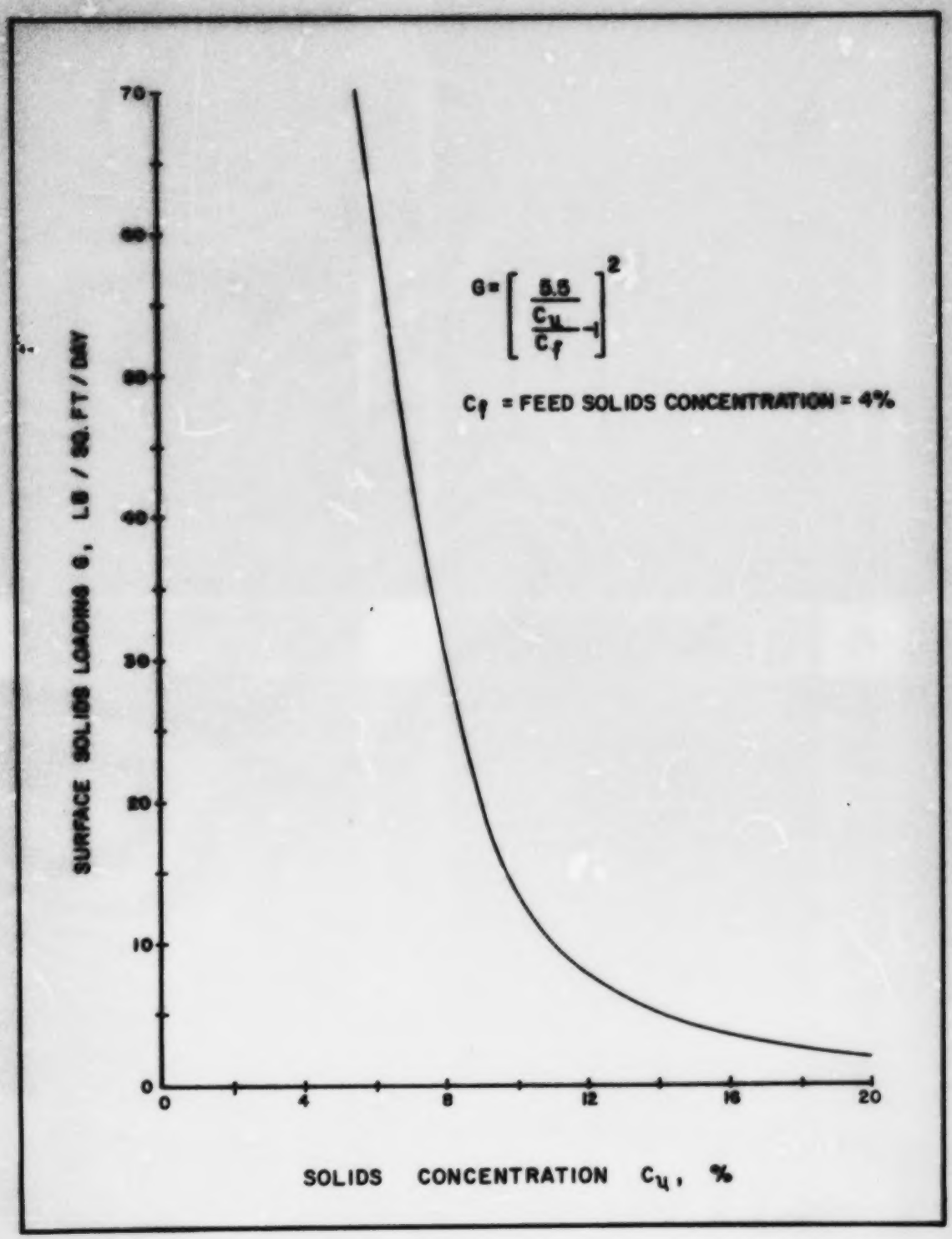

Figure 6: Surface Solids Loading of Gravity Thickener as a Function of Solids Concentration of Thickened Sludge C_u

the surface area. The function for the capital cost has the following form:

$$\bar{Y} = \exp [3.7259 + 0.3977 X + 0.07574 X^2 - 0.001977 X^3 - 0.000296 X^4] \quad [5]$$

where X is the natural logarithm of surface area of the thickener in 1000 ft^2, and the capital cost, $\bar{Y}$, is in \$1000.

The function for the annual operation labor requirement has the form:

$$Y_1 = \exp [5.85656 + .25481 X + .113703 X^2 - .010942 X^3] \quad [6]$$

where Y_1 is the annual payroll man-hours.

The function for the annual maintenance labor requirement, Y_2, has the form:

$$Y_2 = \exp [5.273419 + .22833 X + .122646 X^2 - .011672 X^3] \quad [7]$$

and the annual cost of material and supply in dollars, Y_3, has the form:

$$Y_3 = \exp [5.66988 + .750799 X] \quad [8]$$

The annual operation and maintenance cost was calculated by:

$$OMC = (Y_1 + Y_2)\sigma + Y_3 \quad [9]$$

where σ is the hourly wage rate, assumed at \$8/hr. The most useful expression of the capital cost as well as the operation and maintenance cost is in terms of dollars per ton of dry solids. Then the capital cost per ton of dry solids, $\bar{Y}^*$, is given by:

$$\bar{Y}^* = \frac{CRF(i,n)\ \bar{Y}\ 1000}{365 \times L/2000} \quad [10]$$

where L is solids loading in lbs per day and CRF (i,n) is the capital recovery factor over the design life of n years at the interest rate of i. Values of i=6% and n=25 (hence CRF (6%, 25 years) = 0.0782) were used in all calculations.

The operation and maintenance cost in terms of cost per ton of dry solids is given by:

$$OMC^* = \frac{(Y_1 + Y_2)\sigma + Y_3}{365 \times L/2000} \quad [11]$$

Sludge Holding Tank

There will be hourly as well as seasonal fluctuations in the solids loading of sludge handling equipment at a facility treating ground refuse. Since the operation of a vacuum filter may not be continuous, (e.g., if only operated one shift per day or if not operated over weekends), storage of sludge to equalize the vacuum filter operation is also required. The fluctuation in solids loads if ground refuse is added to sewage is still largely conjectural and therefore we have assumed that a storage and equalization capacity equal to the two and one-half day's production of thickened sludge is sufficient. This would be the necessary capacity to cover weekend production of sludge at one-shift operation. The capacity of the sludge holding tank is thus simply:

$$V_{ht} = 2.5\ Q \qquad [12]$$

where Q is the average daily amount of thickened sludge in gallons.

The equalization and storage of sludge can be accomplished not only by sludge holding tanks, but also by the gravity thickener (if present). The thickening of sludge to the higher concentration requires huge thickeners, and at these concentrations, the thickeners would themselves provide sufficient equalization capacity. Therefore, whenever the volume of sludge holding tank was less than one-fifth the volume of thickeners, the sludge holding tank was deleted from the process chain.

The cost functions for the sludge holding tank were again taken from Patterson and Banker.[27] The function for capital cost has the form:

$$\overline{Y} = \exp\ [2.625751 + .48418\ X + .000613\ X^2 + .002252\ X^3] \qquad [13]$$

where $\overline{Y}$ is in \$1000 and X is the natural logarithm of sludge holding tank volume in 1000 cu ft.

The function for the annual maintenance labor requirement has the form:

$$Y_1 = \exp\ [4.506628 + .21466\ X + .0719\ X^2 - .004681\ X^3] \qquad [14]$$

where Y_1 is the required number of labor hours, and the function for annual operation requirement is:

$$Y_2 = \exp\ [5.72734 + .000762\ X + 0.098\ X^2 - 0.006786\ X^3] \qquad [15]$$

where Y_2 is again in labor hours. Finally, the annual cost of material supply Y_3, in dollars, has the form:

$$Y_3 = \exp\ [5.47994 + .29928\ X + .106\ X^2 - .008658\ X^3] \qquad [16]$$

The capital cost per ton of dry solids, $\overline{Y}^*$, is given by:

$$\bar{Y}^* = \frac{CRF(i,n)\ \bar{Y}\ 1000}{365 \times L/2000} \qquad [17]$$

and the operation and maintenance cost in terms of dollars per ton of dry solids is given by:

$$OMC^* = \frac{(Y_1 + Y_2)\sigma + Y_3}{365 \times L/2000} \qquad [18]$$

where σ is the hourly labor rate and L is the pounds of sludge solids at the thickener per day.

Anaerobic Digestion

Anaerobic digestion of the refuse-sewage sludge is a potentially attractive process for two reasons. First, it provides an opportunity for energy recovery in the form of methane, the potential market for which was examined in the Phase I report. And secondly, it provides a way of destroying volatile solids, thereby reducing the scale of subsequent dewatering and ultimate disposal processes. There has been much recent interest in anaerobic digestion of refuse as a means of mitigating the national energy crisis, and the National Science Foundation held a conference on this topic in June 1973, at which the country's leading researchers in this field presented their latest findings.[28] The consensus of opinion held that anaerobic digestion of refuse was indeed feasible, and that the methane yields would make a substantial contribution to energy supplies. There was some controversy, however, as to the economics of the idea, and it was apparent that no total systems evaluation had yet been undertaken. The uncertainty in the economics of the idea centered around apparently conflicting results of dewatering the subsequent sludge, the need to design the process conservatively in the interest of reliability, and the conflicting opinions as to the mixing characteristics of the digesting sludge.

Golueke[29] reported that 67 percent of the volatile solids and 80 percent of the cellulose of a refuse-sewage sludge mixture were destroyed in a 400 gallon per day (1514 ℓ/d) pilot plant facility. The major problem in operating the unit was the formation of a thick scum layer, and it was considered that only mechanical mixing would suffice to prevent stratification. Dried chicken manure was also added to some of the pilot runs to provide additional nutrients. Pfeffer,[30] reporting on a comprehensive study started at the University of Illinois in 1967, found that refuse and sewage sludge, in the proportions generated by a given population, would need additions of caustic (to keep the pH at acceptable levels) and nutrients for successful digester operation. This was accomplished, however, by the use of inexpensive chemicals. Pfeffer found that the residue dewatered very easily, and experienced no difficulties with mechanical mixing even at digester solids contents of 10 percent (i.e. with feed concentrations of up to 20 percent).

This is in contradiction to the findings of Wise,[31] who found that the digester residue dewatered only with difficulty. However, the refuse-sewage sludge digesters operated by Wise had a solids concentration in the reactor of only 1-2 percent.

Thermophilic digestion appears to have many apparent advantages, according to Cooney,[32] including decreased sludge formation, the destruction of pathogenic organisms, and improved dewatering characteristics of the residue. However, the advantages of thermophilic digestion over mesophilic digestion would be offset by much higher energy costs for heating. Also, some doubts were expressed as to the stability of the operation at these higher temperatures. Nevertheless, Cooney reported successful operation of a solid waste-sewage sludge digester at thermophilic temperatures for over six months.

It might be noted that one of the areas of general agreement among the researchers present at the NSF Conference was that residence times for digestion of refuse would not need to be any greater than those used for digestion of sewage sludge alone. Under anaerobic conditions, most of the cellulose is broken down within the first 5-8 days, and increases of detention time in excess of 20 days resulted in very little additional methane yield.

Mathematical Modelling of the Digestion Process. Although there are several published mathematical models of anaerobic digestion in the literature, those that have been shown to render an accurate simulation are very sophisticated, requiring, for example, knowledge of reaction rates for each major transformation in the multi-stage digestion process.[33] Application of such models to our study was considered, but rejected in view of the deficiencies of data on digestion of refuse. Since the major focus of our investigation is that of cost, we have restricted ourselves to the development of a series of equations that link the major cost determining parameters - solids concentrations, digester capacity, and retention time. We shall assume that a simple first order reaction for the breakdown of volatile solids is an adequate description of the process.

In the development that follows, we shall have occasion to use the following series of mass balance equations. Defining λ as the total solids concentration in the feed, ω as the fraction of volatile solids in the feed, δ as the fraction of volatile solids destroyed, and L the pounds of solids in the feed per day, and assuming a completely mixed reactor, the following relationships hold:

$(1 - \omega)L$	=	$(1 - \omega)L$	
lb inert solids in feed per day		lb inert solids in effluent per day	[19]

$$\omega L = \delta\omega L + (1 - \delta)\omega L \quad [20]$$

lb volatile solids in feed | lb volatile solids destroyed per day | lb volatile solids in effluent per day

$$\frac{L}{\lambda} - L = \frac{L}{\lambda} - L \quad [21]$$

lb water in feed per day | lb water in effluent per day

Computation of Digester Capacity. There are considerable discrepancies in the literature on the subject of digester capacity determination, due in part to the many quasi-empirical formulae in use by environmental engineering practitioners (each of which will, in general, yield a different numerical answer[34]), and in part to the failure to rigorously differentiate between hydraulic retention time and solids retention time. Defining Q_o as the volumetric flow rate of raw sludge to the digester (in cu. ft./day) and Q_e as the volumetric flow rate of digested sludge from the digester, and assuming a specific gravity of sludge solids of unity, then it is clear that:

$$Q_o = \frac{L}{\lambda\ 62.4} = \frac{\left[\frac{\text{lb solids}}{\text{day}}\right]}{\left[\frac{\text{lb solids}}{\text{lb}}\right]\left[\frac{\text{lb}}{\text{cu. ft.}}\right]} = \left[\frac{\text{cu. ft.}}{\text{day}}\right] \quad [22]$$

By reference to the mass balance equations [19] through [21], it is also clear that:

$$Q_e = \frac{\frac{L}{\lambda} - L + (1 - \delta)\omega L + (1 - \omega)\ L}{62.4} \quad [23]$$

$$= Q_o\ (1 - \delta\omega\lambda) \quad [24]$$

The volume of the digester, V, can then be given by the expression:

$$V = Q_o\ t_R = \frac{L\ t_R}{\lambda 62.4} \quad [25]$$

where t_R is the hydraulic detention time. Because δ, ω, and λ are all less than unity, for typical values their product $\delta\omega\lambda$ will be very small (e.g., for δ=0.7, ω=0.5, λ=0.06, $\delta\omega\lambda$=0.021), and hence the error involved in using Q_o in Equation [25], ignoring solids destruction in the reactor, is negligible and conservative.

Computation of Solids Concentrations. Consider next a mass balance of volatile solids, given steady state conditions and a first order reaction. If λ_s is the concentration of volatile solids in the digester, and k is the reaction rate coefficient, then:

$$\underset{\text{lb VS in feed per day}}{\omega L} - \underset{\text{lb VS in effluent per day}}{62.4\ \lambda_s\ Q_e} - \underset{\text{lb VS destroyed per day}}{62.4\ k\ \lambda_s\ V} = 0 \qquad [26]$$

$$\text{hence } \omega L = 62.4\ \lambda_s\ (Q_e + kV) \qquad [27]$$

$$\text{or} \quad \lambda_s = \frac{\omega L}{62.4(Q_e + kV)} \qquad [28]$$

but since $Q_e \tilde{-} Q_o$, and since $V = Q_o\ t_R$

$$\lambda_s = \frac{\omega L}{62.4\ Q_o\ (1 + k\ t_R)} \qquad [29]$$

Finally, by substitution of Equation [22] into this expression,

$$\lambda_s = \frac{\omega\lambda}{(1 + kt_R)} \qquad [30]$$

Note also that comparison of Equations [26] and [20] shows that:

$$62.4\ k\ \lambda_s\ V = \delta\omega L \qquad [31]$$

$$\text{hence:} \quad \delta = \frac{62.4\ k\ \dfrac{\omega\lambda}{(1 + kt_R)} \cdot \dfrac{L\ t_R}{\lambda 62.4}}{\omega L} \qquad [32]$$

$$= \frac{kt_R}{1 + kt_R} \qquad [33]$$

This equation is plotted on Figure 7 for k=0.1, 0.2 and 0.3. Also shown are some experimental results obtained from Pfeffer,[35] from which the k-value may be taken to lie between k=0.1 and k=0.2. We have assumed a k of 0.1 in our subsequent calculations, so that a conservative result is ensured.

Cost Equations. The capital cost of a digester has been found by Eilers to be a function of digester capacity as expressed by the relationship:[36]

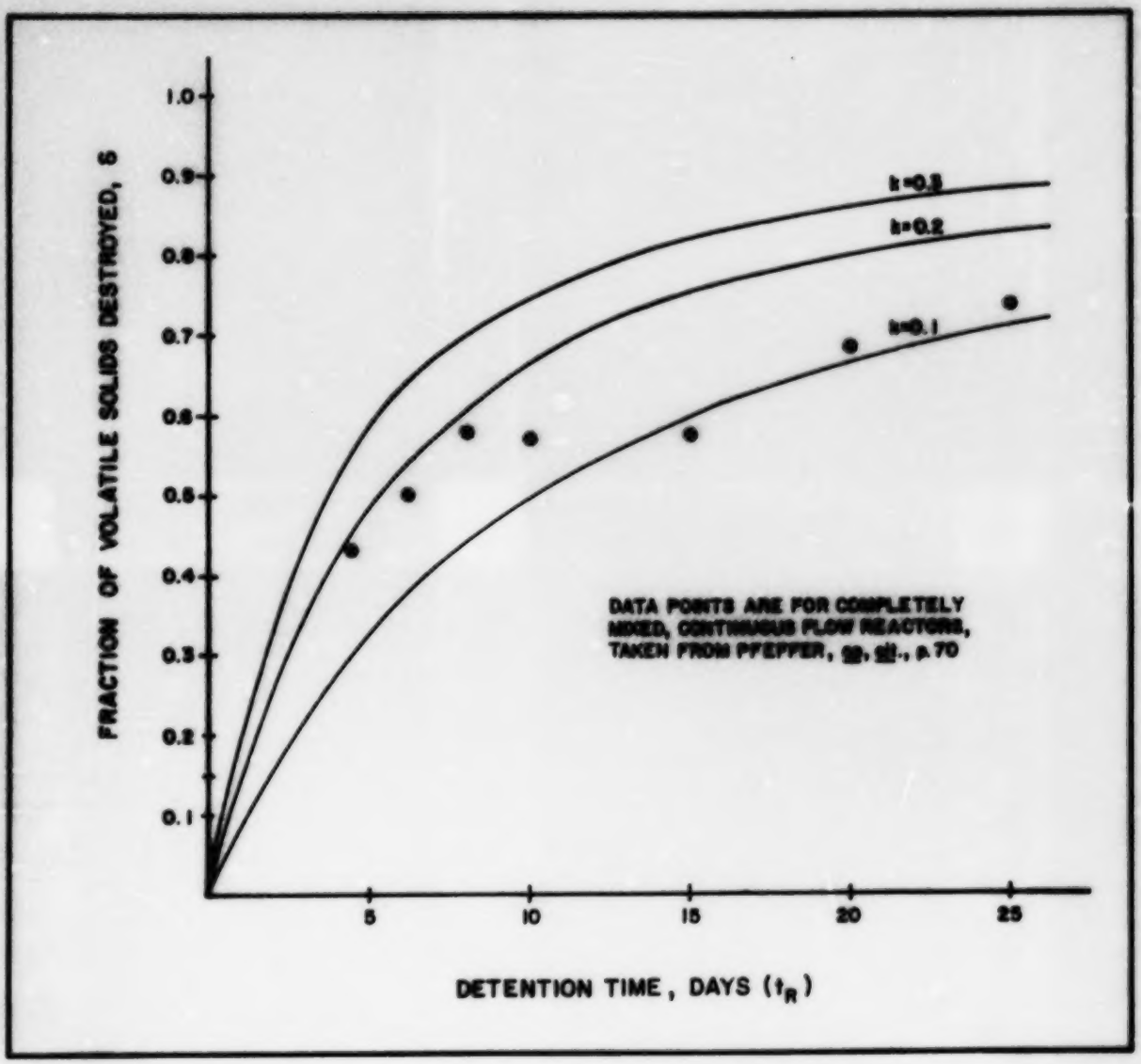

Figure 7: Volatile Solids Destruction

$$\bar{Y} = \exp\left[7.68 - 1.94\ \ln\bar{V} + 0.4\ (\ln\bar{V})^2 - 0.048\ (\ln\bar{V})^3\right] \quad [34]$$

where $\bar{Y}$ is the cost in \$1000 and $\bar{V}$ the capacity of the digester in 1000 cubic feet. Thus by substituting Equation [25] into this cost function one may obtain the capital cost as a function of t_R and λ. The most useful expression of this capital cost is in terms of cost per ton of dry solids: rewriting Equation [34] simply as

$$\bar{Y} = f(\bar{V}) \quad [35]$$

and noting that the tons of solids in the feed per year is given by $365 \times L/2000 = 0.1825L$, then the cost per ton, $\bar{Y}^*$, is given by:

$$\bar{Y}^* = \frac{CRF(i,n)\ f(\bar{V})\ \times\ 1000}{0.1825\ L} \quad [36]$$

where CRF(i,n) is the capital recovery factor over the design life of n years at the interest rate of i.

Finally, the relationship between the total solids concentration of the effluent, λ^* and the influent solids concentration λ can, by reference to Equations [19] to [21], be simply stated as:

$$\lambda^* = \frac{(1 - \delta)\omega L + (1 - \omega)L}{\frac{L}{\lambda} - L + (1 - \delta)\omega L + (1 - \omega)L} = \frac{1 - \delta\omega}{\frac{1}{\lambda} - \delta\omega} \quad [37]$$

where δ is given as a function of residence time t_R and reaction rate coefficient k by Equation [33].

The operating costs of a completely mixed, high rate digester are occasioned by the need to heat both the feed and the digester to an optimal operating temperature, and by the need for mixing. As noted by McFarland, et al.,[37] it is unlikely that external recirculation or gas mixing will be required. A suitable parameter to estimate the power requirement for mechanical mixing is the horsepower per cu. ft. (ϕ). Then the mixing energy Em, is given by:

$$Em = \phi \times V \times 0.746 \times 365 \times 24 \left[\frac{HP}{\text{cu ft}}\right]\left[\text{cu ft}\right]\left[\frac{KW}{HP}\right]\left[\frac{Hrs}{year}\right] \quad [38]$$

$$= 6534\ \phi\ V \left[\frac{kwh}{year}\right] \quad [39]$$

If the cost of power is w cents per kwh, then the annual cost for mixing, Y_m, is given by:

$$Y_m = 65.34\ \phi\ Vw \left[\frac{\$}{year}\right] \quad [40]$$

A rigorous determination of the power requirement ϕ is a somewhat complex undertaking that is beyond the scope of this study. Nevertheless, it is not unreasonable to suggest that ϕ can be approximated as a function of the solids concentration λ^*, because the dynamic viscosity, which largely determines the power requirement, increases with increasing λ^*. In the absence of specific data, a conservative estimate would be:

$$\phi = a_1 \lambda^{*b_1} \qquad [41]$$

where a_1 and b_1 are constants. In order to reproduce such values as are available, both a_1 and b_1 were set at 3.0. At the digester concentrations found in existing practice, say $\lambda^* = 0.04$, ϕ calculates to 1.92×10^{-4} HP/cu ft (50.6 kw/cu.m), which compares conservatively with published values of 1.85×10^{-4} HP/cu.ft[38] (48.7 kw/cu.m). At 10 percent solids concentration, Equation [41] yields a ϕ-value of 30×10^{-4} HP/cu ft (790.2 kw/cu.m), and at 15 percent, a ϕ-value of 101×10^{-4} HP/cu.ft (2660.3 kw/cu.m). This rapid increase of mixing power requirements appears adequately conservative to obtain an upper bound of mixing cost.

Again expressing this mixing cost in terms of a cost per ton, Y_m^*, one obtains:

$$Y_m^* = \frac{65.34\ a_1 \lambda^{*b_1} V_w}{365 \times L/2000} \left[\frac{\$}{\text{ton}}\right] \qquad [42]$$

The computer model also makes an estimate of the energy requirement for preheating the feed to the operating temperature, and for replacing heat losses through the digester walls and the effluent streams. The standard procedures and coefficients described in the WPCF Manual of Practice are used for these calculations.[39]

Methane Gas Production. Several researchers have attempted to estimate methane production from anaerobic digestion of refuse.[40] Pfeffer estimated that 1 lb (0.454 kg) of volatile solids destroyed would yield 7.1 cu ft (0.2 cu.m) of methane. Assuming that 1 ton (0.907 kkg) of raw refuse results in 0.6 tons (0.544 kkg) of sludge solids, and that $\delta = 0.8$ (fraction of VS destroyed) and $\omega = 0.6$ (fraction of VS in the feed, then 1 ton of raw refuse would yield:

$$0.6 \times 0.8 \times 0.6 \left[\frac{\text{tons VS}}{\text{ton}}\right] \times 2000 \left[\frac{\text{lb}}{\text{ton}}\right] \times 7.1 \left[\frac{\text{cu.ft}}{\text{lb VS}}\right]$$
$$= 4089.6 \left[\frac{\text{cu.ft}}{\text{ton}}\right] = 125.9 \left[\frac{\text{cu.m}}{\text{kkg}}\right] \qquad [43]$$

At a heat value of 1000 Btu/cu.ft (9000 kg.cal/cu.m) of methane, one ton (0.907 kkg) of raw refuse will thus produce 4.09 million Btu (1.03×10^6 kg.cal). Pfeffer's estimate of methane production is based on a 15-day detention time.

Dair's estimate is more optimistic, namely 6175 cu ft (173 cu.m) of methane per ton of raw refuse, equivalent to 7.175 million Btu per ton.[41] A city of 250,000 inhabitants might generate 250,000 x 2.25/2000 = 281 tons (254.8 kkg) of raw refuse per day, which would result in 1.73 million cu ft (48400 cu.m) of methane per day. Dair's estimates are based on a 10-day detention time.

McFarland et al.[42] at the University of California found gas production rates in a pilot scale digester to average 7.0 cu ft per lb (0.43 cu.m/kg) of volatile solids added at detention times of about 30 days. This converts to:

$$7.0 \left[\frac{\text{cu ft}}{\text{lb VS}}\right] 0.6 \left[\frac{\text{lb VS}}{\text{lb Sludge}}\right] 0.62 \left[\frac{\text{lb Sludge}}{\text{lb Raw Refuse}}\right] 2000 \left[\frac{\text{lb}}{\text{ton}}\right]$$
$$= 5208 \left[\frac{\text{cu ft}}{\text{ton}}\right] = 160.4 \left[\frac{\text{cu.m}}{\text{kkg}}\right] \qquad [44]$$

or 5.2 million Btu per ton of raw refuse.

In our calculations of the methane gas benefit, we have used a unit price of \$0.80/1000 cu ft (\$28.50/1000 cu.m) and a methane production of 7 cu ft per pound of volatile solids destroyed.

Vacuum Filtration

Vacuum filtration was stated by Metcalf & Eddy to be an especially suitable process for dewatering raw refuse, refuse sludges, and some initial tests showed excellent performance without any need for chemical conditioners. Indeed, it was judged that a vacuum filter might be the only sludge handling unit necessary prior to disposal. All of the process combinations examined in the simulations of this study make use of this unit operation.

The major independent variable of interest is the yield of the vacuum filter, as this allows direct computation of the required filter area which in turn is the primary determinant of capital cost. A commonly accepted expression for the yield, Y, in $\text{lb/ft}^2\text{/hour}$, is:[43]

$$Y = 35.6 \left[\frac{\Delta P \times C^* \times f}{\mu \times R \times \Theta_R}\right]^{0.5} \qquad [45]$$

where: ΔP is the vacuum in psi
C^* is the solids concentration of the cake in gms/ml
f = form time/cycle time
Θ_R = cycle time in minutes = time per drum revolution
$R = r \times 10^{-7}$ sec^2/g where r is the specific resistance
μ = viscosity of the filtrate, centipoises.

Because we are using weight solids concentrations, C^* must be expressed as

$$C^* = \frac{\lambda_f \times 454 \times 62.4}{1000 \times 28.3} = \frac{\left[\frac{\text{lb}}{\text{lb}}\right]\left[\frac{\text{gms}}{\text{lb}}\right]\left[\frac{\text{lb}}{\text{cu ft}}\right]}{\left[\frac{\text{ml}}{\ell}\right]\left[\frac{\ell}{\text{cu ft}}\right]} \qquad [46]$$

assuming a specific gravity of sludge solids of unity and where λ_f is the solids concentration (by weight) of the cake.

It was concluded in Chapter II that the dewatering characteristics of primary sludge from sewage treatment plants handling ground refuse resemble those of chemically conditioned primary sludges. Therefore, for the calculation of vacuum filtration of primary sludge, a value of specific resistance corresponding to the chemically conditioned primary sludges was used, namely $r = 1 \times 10^8$ sec^2/g.

In those simulations that included digestion, the quality of the digested sludge was considered to be the same as the quality of ordinary digested sludge, an assumption that is inherently conservative. Therefore, chemical conditioning of the sludge was included (see later cost functions) and a corresponding value of specific resistance, $r = 1 \times 10^8$ sec^2/g was chosen.

For typical operational conditions of vacuum filtration ($f = 0.4$, 15°C, 12 psi), for a cake solids concentration of 25 percent, and for the specific resistance value of $r = 1 \times 10^8$ sec^2/g, the yield of the vacuum filtration operation is then a function of feed concentration and the time per revolution of the (rotary) vacuum filter. In the absence of any experimental data on optimum drum revolution time, we have assumed a value of 3 minutes. The curve for $\Theta_R = 3$ on Figure 8 therefore shows the function for the yield of the vacuum filter as used in our study. The validity of all these assumptions may be gauged by comparison with other published values as shown on Table 2.

Cost Functions. Cost functions for vacuum filtration were again taken from Patterson and Banker.[44] The capital cost of a vacuum filter is a function of the filter surface area and can be stated as:

$$\bar{Y} = \exp\,[3.288 + 0.1945\,W + 0.0383\,W^2] \qquad [47]$$

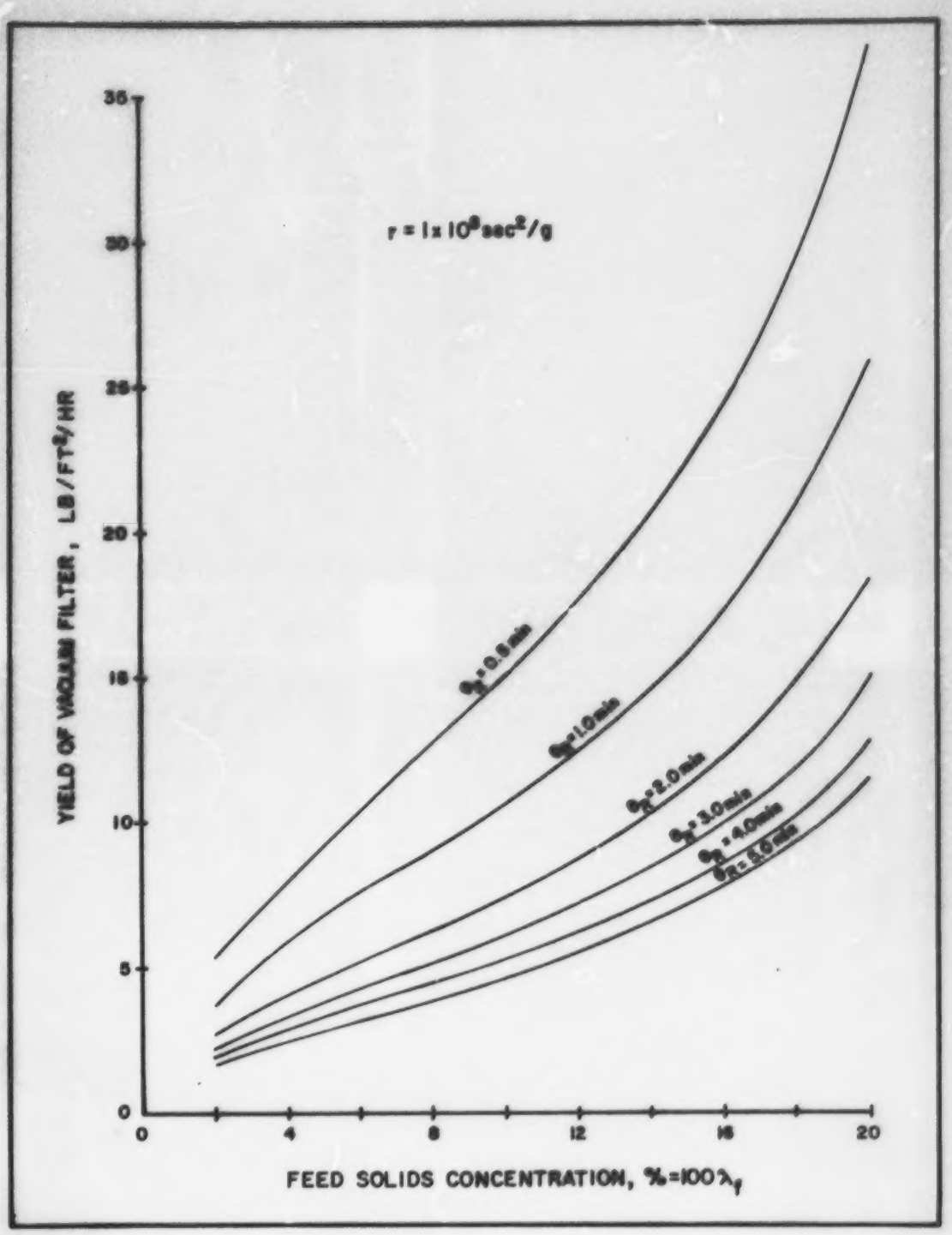

Figure 8: Yield of Vacuum Filter as a Function of the Feed Concentration and the Time of One Revolution of a Drum

Type of Sludge	Chemical Conditioning	Solids Concentration		Vacuum Filter Yield	Source of Information
		Initial %	Final %	lb/sq.ft./hr.	
Raw Primary	$FeCl_3$, Lime	7.57	20.1	6.91	Process Design Manual For Upgrading Existing Wastewater Treatment Plants, EPA, Technology Transfer.
Raw Primary	$Fe_2(SO_4)_3$, Lime	9.1	24.0	8.6	
Raw Primary	$FeCl_3$, Lime	15.0	40.0	5.0	
Raw Primary	$FeCl_3$, Lime	11.2	39.0	3.1	
Raw Primary	Lime, Copperas	3.5		2.	Gale, R.S., Some Aspects of the Mechanical Dewatering of Sewage Sludges, Filtration Separation, March/April 1968, pp. 133-144.
Raw Primary	Lime, Copperas	7.		5.	
Raw Primary	Conditioned	Design Filter Rate 4 to 12			WPCF Manual of Practice No. 8, Sludge Dewatering and Disposal
Raw Primary	$FeCl_3$, Lime	8.6	35.3	3.	Sludge Concentration, Filtration and Incineration, Continued Education Service, 109 South Observatory Street, Ann Arbor, Michigan.
Raw Primary	Lime	7.1	29.6	5.94	
Raw Primary	Lime	5.6	30.6	5.06	

Table 2: The Yield of Chemically Conditioned Primary Sludges

where $\overline{Y}$ is the capital cost in $1000 and W is the natural logarithm of filter surface area in square feet.

The manpower requirements as well as material and supply costs can be given as functions of the tons of dry solids handled per year. Thus the function for the annual operation and maintenance labor requirement has the form:

$$Y_1 = \exp [4.306 - .0937 X + 0.048 X^2] \quad [48]$$

where Y_1 is the annual labor man-hours and X the natural logarithm of dry solids filtered in tons/year.

The annual cost of chemicals, which are assumed to be necessary only for filtration of digested sludge, has the form:

$$Y_2 = \exp [-3.5729 + 0.8457 X] \quad [49]$$

and the annual cost of other material and supply requirements has the form:

$$Y_3 = \exp [-3.11 + 0.7185 X] \quad [50]$$

where Y_2 and Y_3 are in dollars and X is the natural logarithm of dry solids filtered in tons/year.

The operation and maintenance cost in the terms of dollars per ton of dry solids is given by:

$$OMC^* = \frac{Y_1\sigma + Y_2 + Y_3}{365 \text{ L}/2000} \quad [51]$$

and the capital cost per ton of dry solids is given by:

$$\overline{Y}^* = \frac{CRF(i,n)\ \overline{Y}\ 1000}{365 \text{ L}/2000} \quad [52]$$

Sludge Haul by Truck

The only means of transporting the sludge cake from the sewage treatment plant to the sanitary landfill site considered by this analysis is truck haul. There are, of course, other alternatives for sludge transport, including rail haul or even pipeline transport, but these were not considered in view of the special circumstances that would need to be present for such options. Moreover, the sludge cake produced by an efficient dewatering operating would lend itself very readily to truck haul, especially over short distances.

The need to consider sludge transportation is clear in view of the great increase in sludge quantities expected, which, in general, would make the search for a site near the treatment facility much more difficult. And even if a treatment facility already practices landfill disposal at an adjacent site, it cannot be generally expected to suffice for the additional sludge quantities likely to be produced at a treatment facility handling ground refuse.

A numerical example will serve to illustrate this need for transportation facilities. A 10 mgd (37850 cu.m/day) sewage treatment facility might serve 100,000 persons, and hence generate:

$$100{,}000 \text{ [persons]} \; 0.15\left[\frac{\text{lb. solids}}{\text{cap. day}}\right] 365 \left[\frac{\text{days}}{\text{year}}\right] = 5.47 \times 10^6 \left[\frac{\text{lb. solids}}{\text{year}}\right] = 2.48 \times 10^6 \left[\frac{\text{kg. solids}}{\text{year}}\right] \quad [53]$$

Assuming a vacuum filter cake of 25 percent solids ($\lambda = 0.25$) then the annual volume is:

$$\frac{5.47 \times 10^6 \left[\frac{\text{lb. solids}}{\text{year}}\right]}{62.4\left[\frac{\text{lb}}{\text{cu ft}}\right] 27 \left[\frac{\text{cu ft}}{\text{cu yd}}\right] 0.25 \left[\frac{\text{lb solids}}{\text{lb}}\right]} = 1.29 \times 10^4 \text{ [cu yds]} \quad [54]$$

$$= 0.98 \times 10^4 \text{ [cu.m]}$$

An analogous calculation, using a figure of 1.4 lb (0.64 kg) of sludge solids per capita per day generated by adding ground refuse to the sewage, would result in 51.1×10^6 lbs. solids/year (23.2×10^6 kg/yr). Assuming that the sludge is digested, that $X = \delta\omega = 0.60$ of the total solids are destroyed by digestion and that the subsequent vacuum filter cake has a 30 percent solids content, then the annual fill volume required is:

$$\frac{51.1 \times 10^6 [1 - 0.60]}{62.4 \times 27 \times 0.3} = 4.04 \times 10^4 \text{ [cu yds]} \quad [55]$$

$$= 3.09 \times 10^4 \text{ [cu.m]}$$

Thus under these typical conditions the annual landfill capacity requirement increases three-fold over the requirement of a treatment facility already practicing sludge landfill disposal. Moreover, some additional fill volume would be necessary for the increased amounts of grit.

The model used to simulate truck haul of the vacuum filter cake is based on the following series of equations. First, consider the theoretical volume of cake produced per year, V, which can be expressed as:

$$V = \frac{\Psi_f \, 365}{\lambda_f \, 62.4 \times 27} \qquad [56]$$

$$= 0.216 \frac{\Psi_f}{\lambda_f} [\text{cu yds}] \qquad [57]$$

where: Ψ_f = lb. of dry sludge solids per capita per day in the vacuum filter cake

λ_f = solids content of the vacuum filter cake

If a truck of capacity Q cubic yards is used for haulage, then the number of trips per year, n, is given by:

$$n = \frac{0.216 \, \Psi_f}{\lambda_f Q \eta} \qquad [58]$$

where η is the efficiency of truck volume use. η will in general be less than unity, because of difficulty in fully utilizing the entire theoretically available volume caused by the rigidity of a cake with little free moisture.

If the distance of the disposal site to the treatment plant is d miles; if the average truck speed is S mi/hr (1.6S km/hr); and if the hours for loading and unloading are ℓ and u, respectively, then the time of one trip in hours is given by:

$$t_{trip} = \frac{2d}{S} + \ell + u \qquad [59]$$

Thus if 2100 hours of operation are available per truck per year, the number of trucks required, M, is given by:

$$M = \frac{t_{trip} \, n}{2100} \qquad [60]$$

and hence the total annual cost of operation is given by:

$$= t_{trip} \cdot n \cdot \sigma + M^{\nabla} \cdot C \cdot CRF(i,n) \qquad [61]$$

where σ is the cost of operation in \$/hour (including labor and gas), C is the capital cost per truck, and CRF(i,n) is the appropriate capital recovery factor, and M^{∇} the integer next larger than M.

Sludge Disposal by Landfill

Metcalf & Eddy concluded that the sludge produced by the dewatering methods tested would be quite amenable to disposal by landfill, with little free water remaining in the semi-rigid cake.[45] It should be noted, however, that several states presently prohibit the landfilling of undigested sludge from wastewater treatment plants, and the proposed EPA guidelines for land disposal of solid wastes stipulate that digested sewage sludge may not contain any free moisture.[46]

A comparison between the landfill volume required for landfilling, of, say, 100 tons (90.7 kkg) of compacted raw municipal refuse and the landfill volume required for landfilling an equivalent amount of sludge as produced at the treatment plant if the refuse were ground and added to the sewer, is very instructive. Assuming 100 tons of refuse has a 20 percent moisture content, 10 percent nongrindables and 7.5 percent grit, then the sludge produced by primary treatment would contain 64 tons (58 kkg) of dry solids per 100 tons of raw refuse. If this is converted to a sludge of 30 percent moisture content, then assuming a specific gravity of 1.0 for the solids, the weight of sludge is 213 tons (193.2 kkg), whose volume equals:

$$\frac{213[\text{tons}] \times 2000\left[\frac{\text{lb}}{\text{ton}}\right]}{62.4\left[\frac{\text{lb}}{\text{cu ft}}\right] \times 27\left[\frac{\text{cu ft}}{\text{cu yd}}\right]} = 252.8[\text{cu yds}] = 193.3[\text{cu.m}] \qquad [62]$$

On the other hand, raw refuse is normally compacted to an in-place density of 800 lb/cu yd (475.2 kg/cu.m); hence, 100 tons of compacted raw refuse would occupy 250 cu yds of landfill volume.

However, the fill requirement of the sludge is very sensitive to the moisture content of the sludge, and, in the case that digestion is used, to the fraction of volatile solids in the feed and the fraction of volatiles destroyed. If a sludge of solids content λ were produced, then the fill volume, V^*, per 100 tons of raw refuse is:

$$V^* = \frac{64 \times 2000}{\lambda \times 62.4 \times 27} = \frac{73}{\lambda}[\text{cu yds}] \qquad [63]$$

Now suppose that a digester were used to destroy a fraction δ of the volatile solids, and that ω is the fraction of volatiles in the solids of the digester feed. Then the solids per 100 tons (90.7 kkg) remaining are given by:

$$64[1 - \delta\omega] \qquad [64]$$

and hence the fill volume, V^*, is given by:

$$V^* = \frac{73}{\lambda} [1 - \delta\omega] \qquad [65]$$

Suppose that 70 percent of volatile solids are destroyed [$\delta = 0.7$] and that the dry solids have an 80 percent volatile solids content. Then if $\lambda = 0.30$, Equation [65] yields a fill volume of 107.06 cu yds, (81.9 cu.m), of half the landfill volume required by the compacted raw refuse. Thus, one may conclude that landfill volume requirements for sludge disposal will be no higher than that required for landfilling raw refuse. Moreover, if the solids content can be increased beyond 30 percent, the fill requirements drop rapidly. This is shown on Figure 9 which plots the decrease in land requirement over raw refuse landfilling as a function of the solids content and the solids destruction factor X, defined as:

$$X = \delta\omega \qquad [66]$$

But, although the fill volume may thus be less than for landfilling of the raw refuse, this advantage is offset by the possible need for sludge haul, as discussed in the previous section.

For purposes of model simulation, the annual landfill area requirement is given by:

$$\text{AREA} = \frac{V}{\mu \times th \times 43560} = \frac{\left[\frac{\text{cu ft}}{\text{year}}\right]}{[\text{ft.}]\left[\frac{\text{sq.ft.}}{\text{acre}}\right]} = \left[\frac{\text{acre}}{\text{year}}\right] \qquad [67]$$

where V is the annual volume requirement in cu ft, as given by Equation [56], th is the thickness of the lift, and μ is the fraction of the lift thickness occupied by sludge. The calculations assume an 8-foot (2.44 m) lift, of which 2 feet (0.61 m) is assumed to be earth cover, and hence $\mu = 0.75$. In order to avoid complex problems associated with land purchase arrangements, the land costs are obtained simply by multiplication of the annual land requirement by a per acre figure, assumed in these computations to be $1000/acre. Operation costs of the landfill operation are based on the total tons handled per year as given by Figure 10.

Incineration

Because the dewatered sludge has a high content of combustible material, it should be amenable to incineration. In most cases, the heat of combustion of sewage sludge lies near 10,000 Btu per pound (5550 kg cal/kg) of volatile solids, but whether or not additional fuel will be needed for incineration depends mainly on the amount of water left in the sludge after vacuum or mechanical filtration, the presence of filter aids, and whether the sludge is raw or has undergone anaerobic digestion (which converts some of the combustible

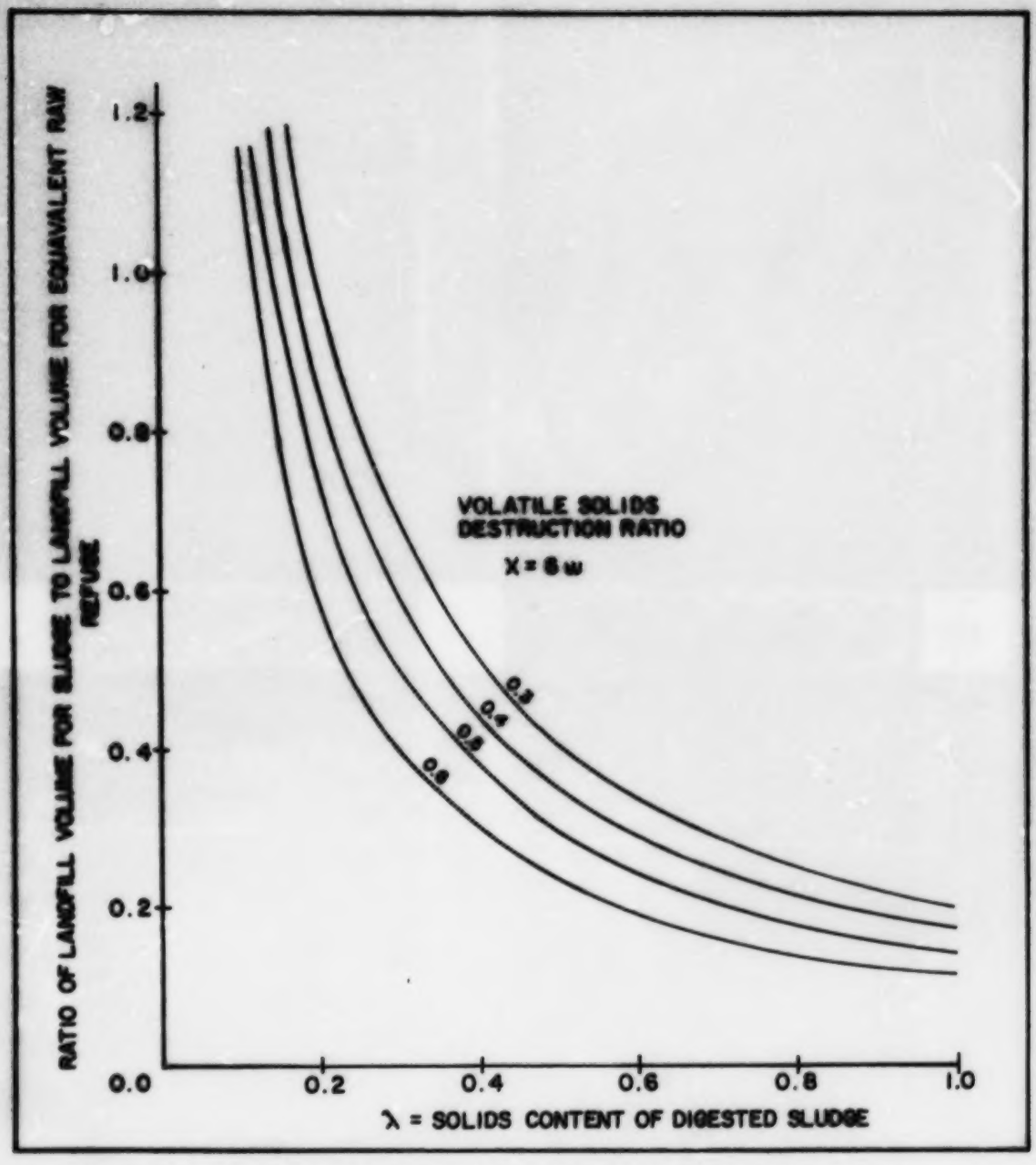

Figure 9: Landfill Volume as a Function of Sludge Solids Content and Volatile Solids Destruction

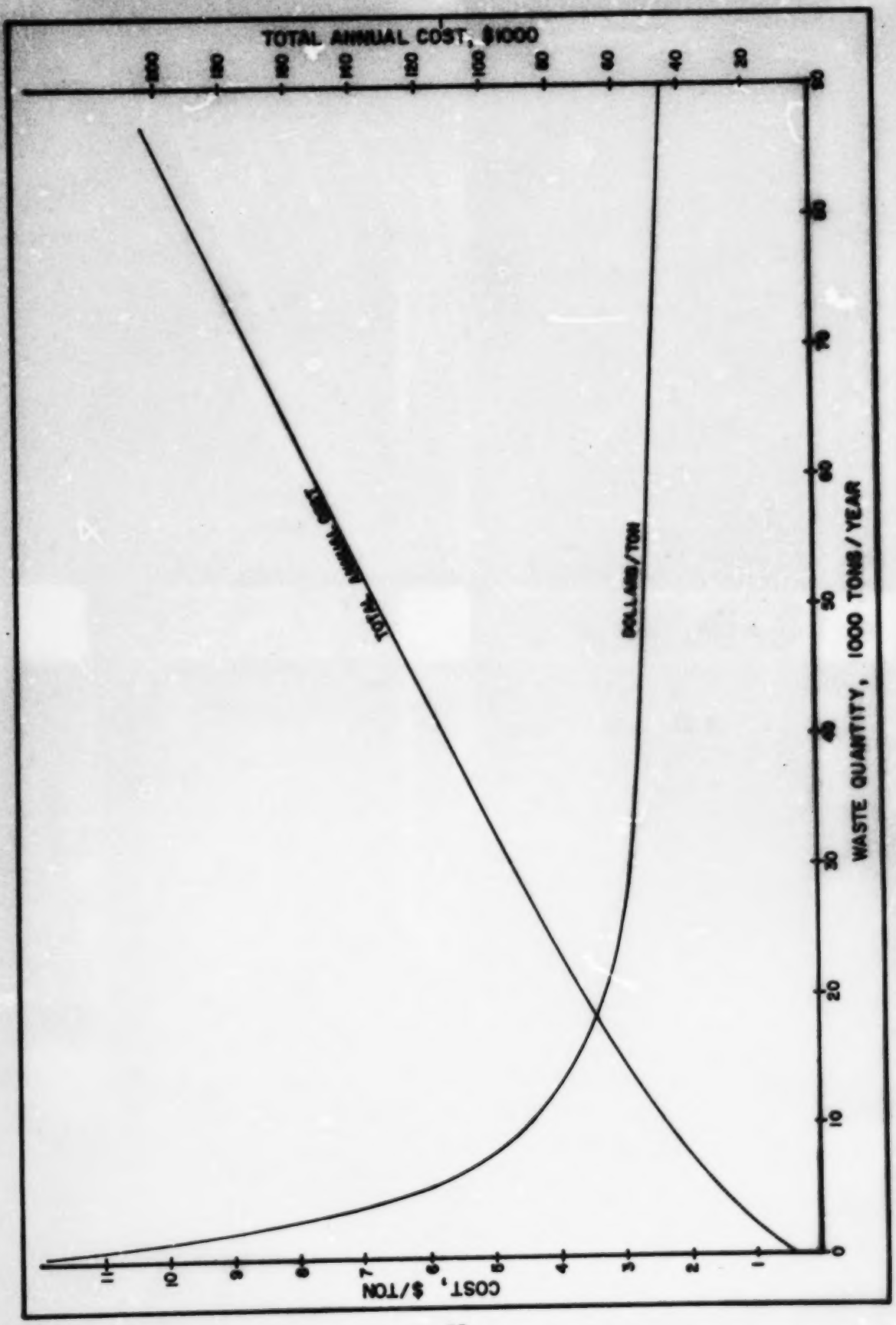

Figure 10: Cost of Sludge Landfill

solids to methane and carbon dioxide). In general, no supplementary fuel is needed when the solids content exceeds some 25 to 30 percent and a volatile solids content of 70 percent by weight.[47] Thus a sludge with 70 percent volatile solids might have a heat value of about 7,000 Btu/lb (3885 kg cal/kg) of total dry solids. Other sources quote heat values of about 7,800 Btu/lb (4329 kg cal/kg) dry solids for primary sludge and 6,500 Btu/lb (3607.5 kg cal/kg) for secondary sludge.[48]

Raw refuse has a heat value often quoted at around 6,000 Btu/lb (3330 kg cal/kg) of raw refuse;[49] converting this into a treatment plant sludge from which grit and metals are excluded results in a heat value of about 7,300 Btu/lb (4051.5 kg cal/kg) dry solids, which is of the same order of magnitude as the sewage sludges. Thus the sludge produced from treating ground refuse in sewage should also be self-combustible at solids contents of 25 percent and above, and incineration would not require an auxiliary fuel.

The cost functions for incineration were again taken from Patterson and Banker.[50] The capital cost (in $1000) is a function of dry solids incineration capacity and has the form:

$$\bar{Y} = \exp(26.143211 - 10.5903\ X + 1.9969\ X^2 - .1605\ X^3 - .00257\ X^4] \quad [68]$$

where X is the dry solids incineration capacity in lb/hr.

The annual operation labor requirement was calculated using the equation:

$$Y_1 = \exp[-5.2046 + 5.8538\ X - 1.0787\ X^2 + .08985\ X^3 - .00257\ X^4] \quad [69]$$

where X = the amount of dry solids incinerated in tons/yr.
Y_1= the annual payroll manhours.

The function for the annual maintenance labor requirement has the following form:

$$Y_2 = \exp[-7.4589 + 6.828\ X - 1.2958\ X^2 + .1102\ X^3 - .003249\ X^4] \quad [70]$$

where X = the amount of dry solids incinerated in tons/yr.
Y_2= the annual payroll manhours.

The annual cost of electric power and auxiliary fuel costs in dollars was calculated by:

$$Y_3 = \exp[-4.46114 + 6.2450\ X - 1.1778\ X^2 + .09842\ X^3 - .002876\ X^4] \quad [71]$$

where X = the amount of dry solids incinerated in tons/yr.

The annual cost of material and supplies in dollars was calculated by:

$$Y_4 = \exp[-9.9923 + 9.5037\ X - 1.9302\ X^2 + .17385\ X^3 - .005599\ X^4] \quad [72]$$

where X = the amount of dry solids incinerated in tons/yr.

Supplementary fuel oil would be needed only when incineration of digested sludge is considered. As the lost combustion heat due to the digestion must be substituted by supplementary oil, the amount of fuel oil required was calculated by:

$$OIL\left[\frac{\text{tons of oil}}{\text{year}}\right] = \frac{(1-\delta)\omega\ L[\text{lb/day}] \times 360[\text{day/yr.}]}{2000[\text{lb/ton}]} \times \frac{10{,}000[\text{Btu/lb of volatile solids}]}{14{,}900[\text{Btu/lb of oil}]} \quad [73]$$

The cost of additional oil was calculated using a unit heating oil price of 21.7¢/gal (5.7 ¢/ℓ), or about $65/ton ($71.66/kkg).

Hence the total annual OMR cost for incineration, OMR_I, is given by:

$$OMR_I = (Y_1 + Y_2)\,\sigma + Y_3 + Y_4 + OIL \times 65 \times \Omega = [\$/\text{yr.}] \quad [74]$$

where $\Omega = 1$ if digested sludge is incinerated; $\Omega = 0$ otherwise, and σ is the labor cost in $/hour.

CHAPTER IV

SIMULATION STUDIES

Introduction

In order to keep the simulation efforts within reasonable time and cost limits, four likely process configurations were selected in advance. The four alternatives selected all purposely involve only traditional technologies. This is justified on the basis that cost functions for many of the newer processes such as wet oxidation or pyrolysis are not presently available in the absence of a sufficiently widespread practical experience. But more importantly, perhaps, is the inability to make predictions of process performance. Whilst it is relatively easy to predict the consequences of ground refuse addition to, say, thickening or vacuum filtration, in the absence of even laboratory data, similar predictions for the more sophisticated technologies would be quite speculative. Indeed, we are already at the limit of reasonable prediction by including digestion as one of the alternatives.

This is in no way to imply that these technologies are inferior or even more expensive than the traditional ones to which we have addressed our detailed analysis. Rather, our goal is to establish a reasonably accurate picture of the costs involved in the handling and disposal of ground refuse sludges, in order that the economics of the entire wet systems concept can be established.

Considerations in the Selection of Alternative Process Configurations

As noted in Chapter II, there is a dramatic increase in the ratio of primary to secondary sludge at a facility accepting ground refuse. Moreover, it was concluded that the addition of secondary sludge to the very much larger quantity of primary sludge would not alter the latter's physical-chemical characteristics. Consequently, separate treatment of these sludges does not appear reasonable. Many new treatment plants provide different treatment processes for primary and secondary sludge streams; for example, the 64 mgd (2.42×10^5 cu.m/day) facility about to be built in Springfield, Massachusetts, will use air floatation thickening for the waste activated sludge and gravity thickening for the primary. It is questionable whether such a configuration would be beneficial for handling ground refuse sludges, especially from the viewpoint of scale economies. Therefore, the initial operation for all process configurations is a mixing of the two sludge streams.

Because activated sludge is currently the most widespread secondary treatment method, we have restricted our focus to that particular source of secondary sludge. The assumption of a 1 percent solids concentration of the waste activated sludge may well be questioned, but

in view of the wide diversity of concentrations encountered in practice, and the fact that the much higher primary to secondary sludge ratio tends to make subsequent computations relatively insensitive to the assumed secondary concentration, the 1 percent figure does not appear unreasonable.

The impact of the addition of advanced waste treatment processes to a secondary treatment plant must doubtless be considered in the very near future. And while the sludge production varies considerably with the process selected, there is as yet insufficient information upon which to base a rational choice of advanced waste treatment at a plant handling ground refuse. Consequently, we may rationalize our omission of advanced treatment sludges not only on the basis that the quantity involved would be small in comparison to that from the ground refuse (that will settle as primary sludge), but also that the uncertainties involved are still too great for the selection of any one process to have real meaning.

Alternative 1

This first process configuration is shown on Figure 11, and is similar to one of the sludge handling alternatives suggested by Metcalf & Eddy in their preliminary studies.[43] However, we have added the option of gravity thickening to the basic configuration of holding tank and vacuum filter in view of some preliminary simulation runs that showed the advantage of concentration increases prior to vacuum filtration. However, the results of the subsequent optimization will show that at optimal operational conditions of the thickener, we can dispense with the sludge holding tank (and hence the holding tank is shown on Figure 11 with a dashed line).

Variations in Solids Concentrations. The first series of simulations used a refuse generation rate of 2.25 lb/cap/day (1.135 kg/cap/day), a population of 100,000, a landfill located 10 miles distant, and the concentration of the thickened sluge, C_u, as the principal independent variable. The results of this simulation are shown on Figure 12, in terms of $/ton dry solids, for each individual unit operation as well as for total cost. Note that the latter is quite insensitive to variations in C_u as the beneficial impact of higher concentrations to the vacuum filter is almost exactly balanced by the increased cost of thickening. Note also that the assumption of a constant 30 percent vacuum filter cake implies constant truck haul and landfill costs. Sludge holding tanks are not required for large C_u because large C_u imply very large thickening tanks that themselves provide adequate equalization capacity.

Economies of Scale. The above simulations were next repeated for facilities corresponding to populations of between 10,000 and 1 million, with the total costs shown as a function of C_u on Figure 13. The cost minimum is more pronounced as the size of the facility decreases.

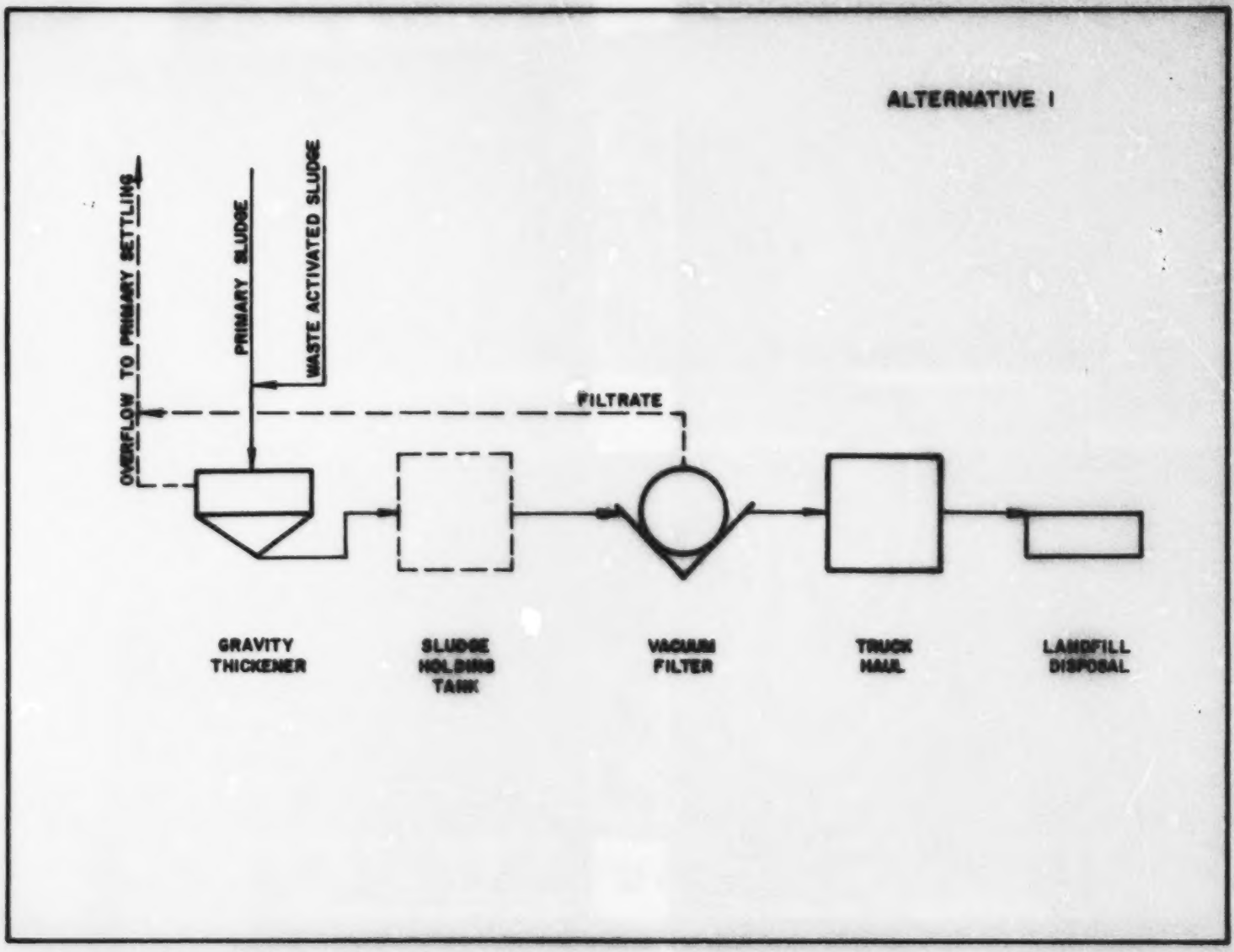

Figure 11: Sludge Handling, Alternative 1

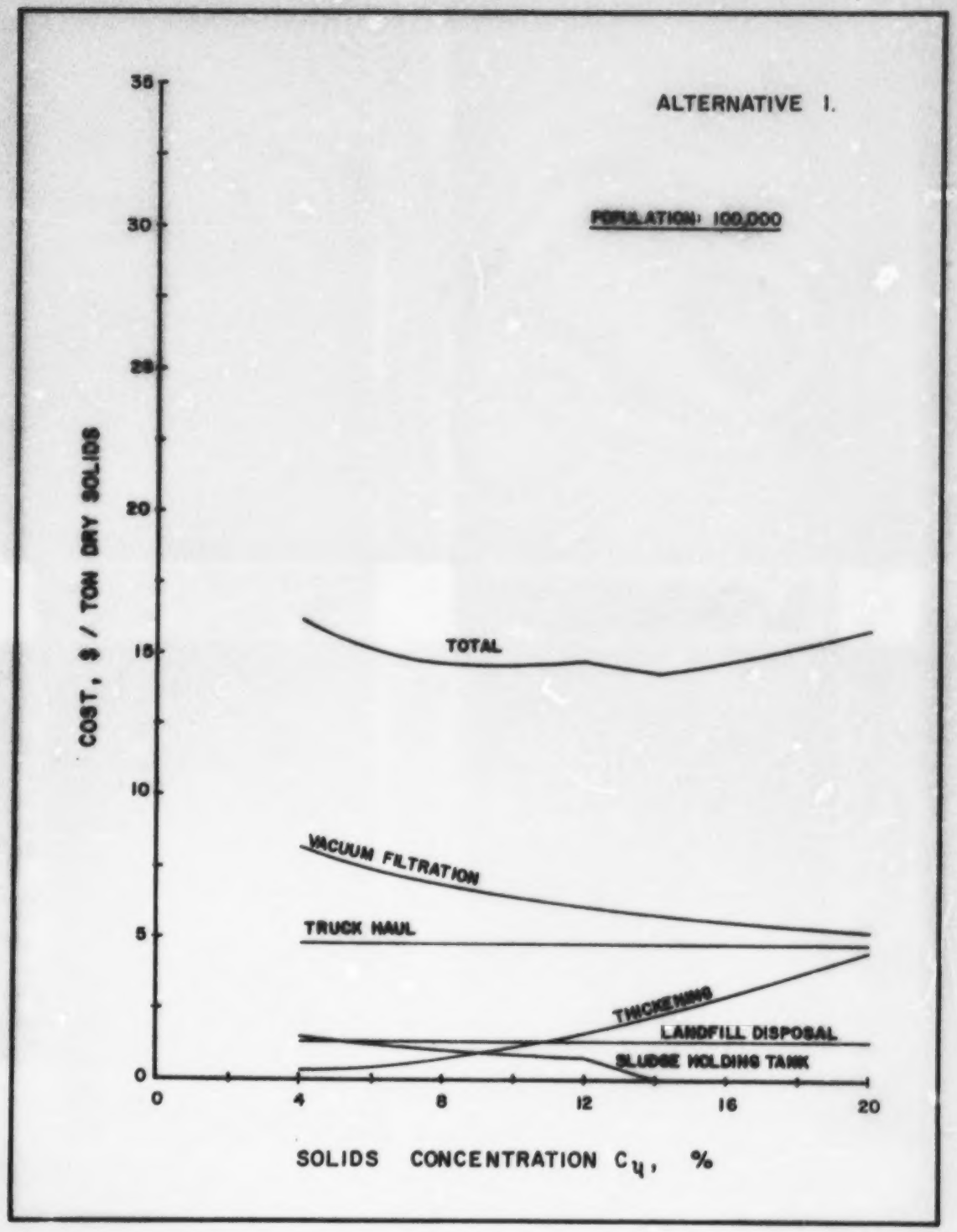

Figure 12: Cost of Particular Processes of Alternative 1 as a Function of Concentration of Thickened Sludge

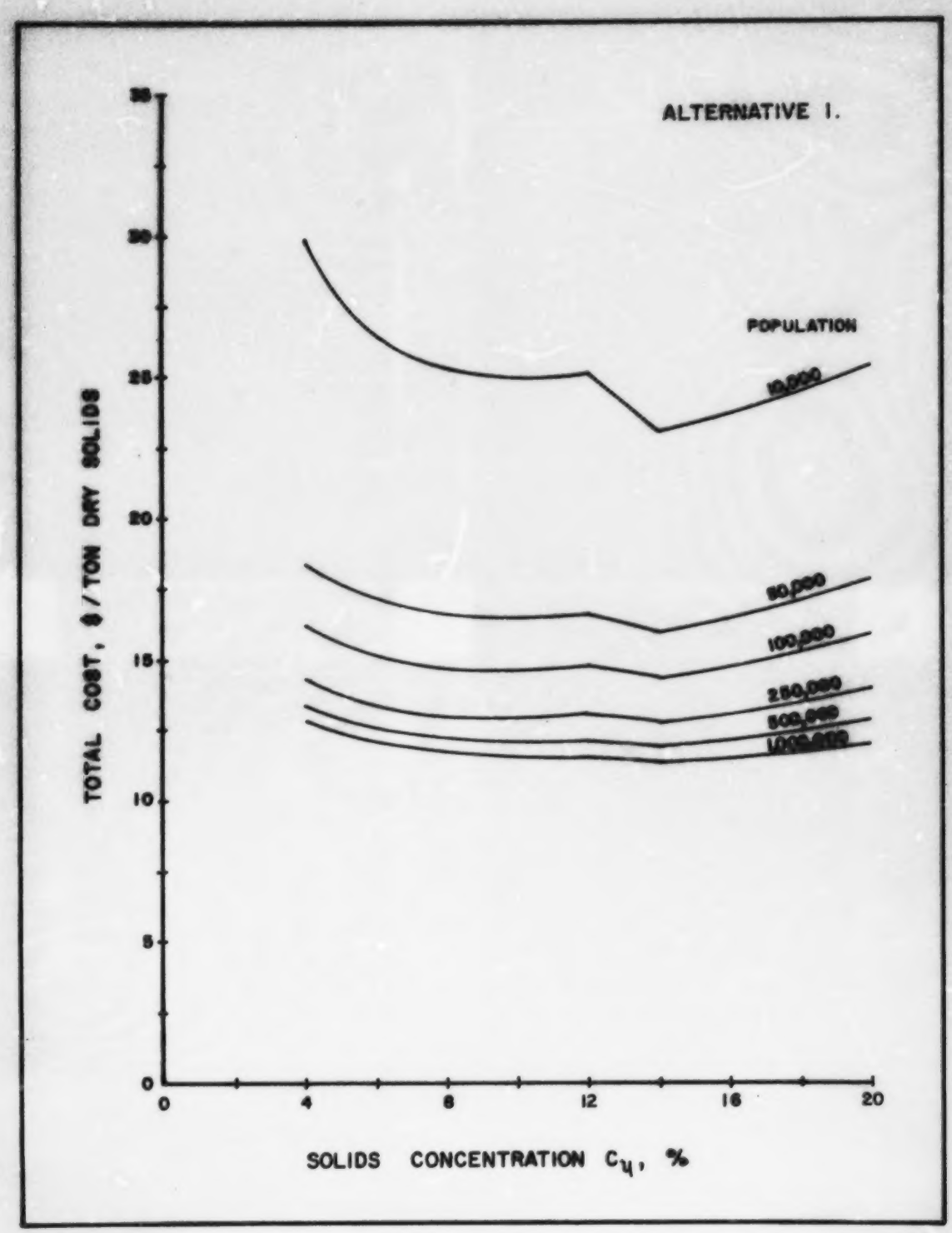

Figure 13: **Total Cost of Sludge Handling (Alternative 1) as a Function of Concentration of Thickened Sludge**

Increasing the per capita refuse generation rate has a generally similar cost impact to increases in population served. By reference to Figure 14 it can be seen, for example, that an increase of refuse generation rate from 2 lb/cap/day to 4 lb/cap/day (.9 to 1.8 kg/cap/day) at a population of 200,000 (along AB) has the same cost impact as increasing population from 200,000 to 600,000 (along AC). The nonlinearity of this equivalence is due to the different proportions of primary to secondary sludge involved.

Also shown on Figure 14 is the cost function for a facility treating only sewage. It lies well above the curves indicated for ground refuse treatment, a circumstance readily explicable in terms of the much lower ratio of primary to secondary sludge encountered at a sewage treatment facility.

Haul Distance and Land Requirements for Disposal. The impact of haul distance on total costs is shown on Figure 15, which, given the linear cost function outlined in Chapter III, is directly proportional to distance. On the assumption of a vacuum filter cake of a constant 30 percent solids concentration, the landfill area required is a function of population size and refuse generation rate. These relationships are shown on Figure 16, assuming a 6 ft. (1.83 m) depth of landfill. At the solids concentration assumed, further dewatering and compaction is unlikely. Clearly the necessary land area is much greater than that required for the disposal of sewage sludge alone, and this might imply greater haul distances in order for a suitable site to be found.

Alternative 2

The process configuration of Alternative 2, shown on Figure 17, has added a digester prior to dewatering. There are three reasons for considering anaerobic digestion: firstly, many states prohibit land disposal of undigested sludge, in which case Alternative 1 may not be realistic; secondly, about 50 percent less land will be required in a subsequent landfill operation because of the destruction of solids; and thirdly, the potential for energy recovery by means of methane yields is very attractive in view of the acute natural gas shortages predicted for many areas of the country.

Detention Time and Solids Concentration. Figure 18 shows the impact of detention time and solids concentration in the digester feed. Again, there is an optimum at around C_u = 14%, corresponding to a solids concentration in the digester of about 6 percent. Note that there is progressively less sensitivity in cost to C_u as residence times decrease; at low residence times, much less digester capacity is required, evidently sufficient to offset the lesser degree of solids destruction. However, at lower residence times, methane yields are also less, a point to which we return below. Although one might conclude from Figure 18 that there is little point in raising detention

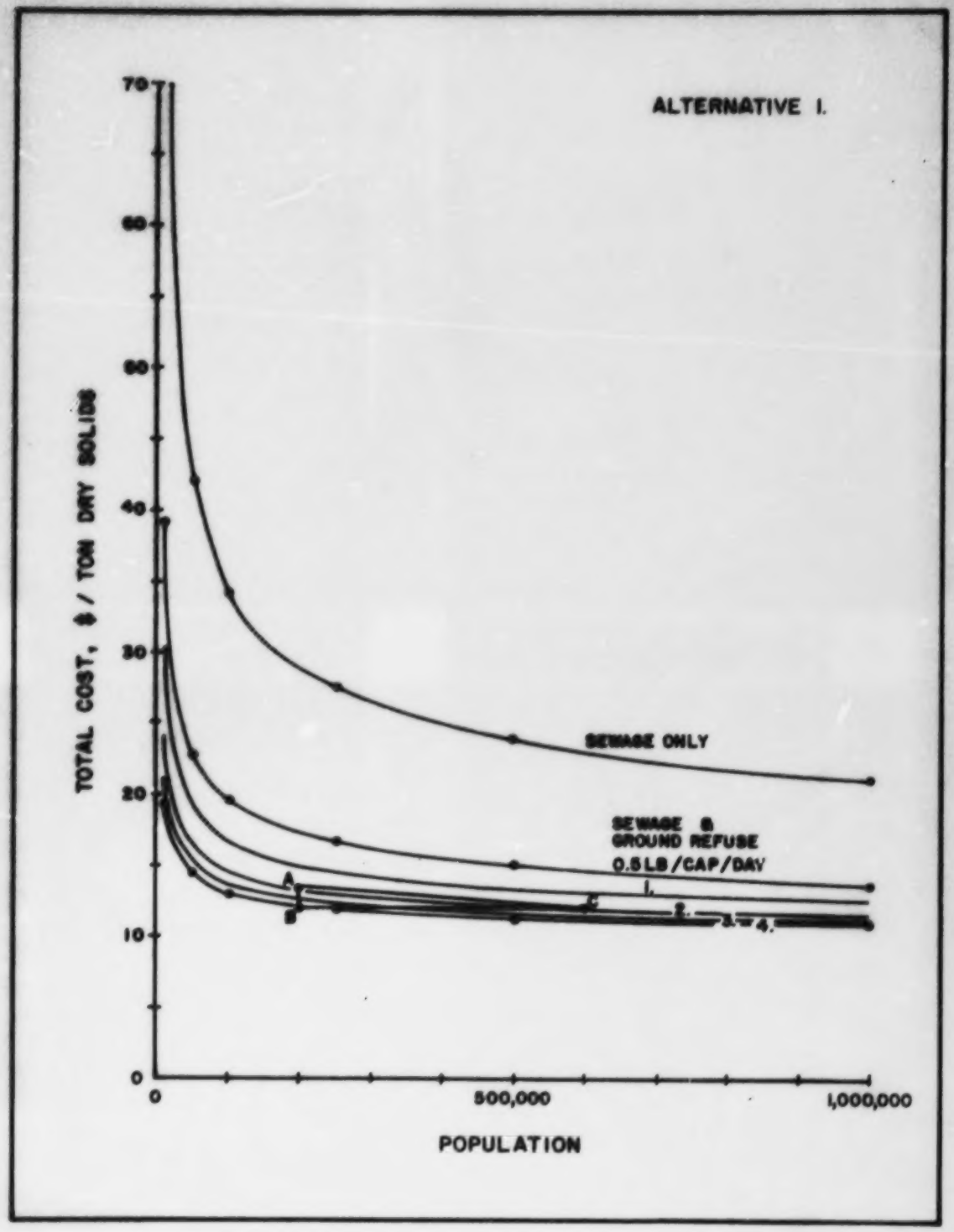

Figure 14: Total Cost of Sludge Handling (Alternative 1) as a Function of Population and Refuse Generation Rate

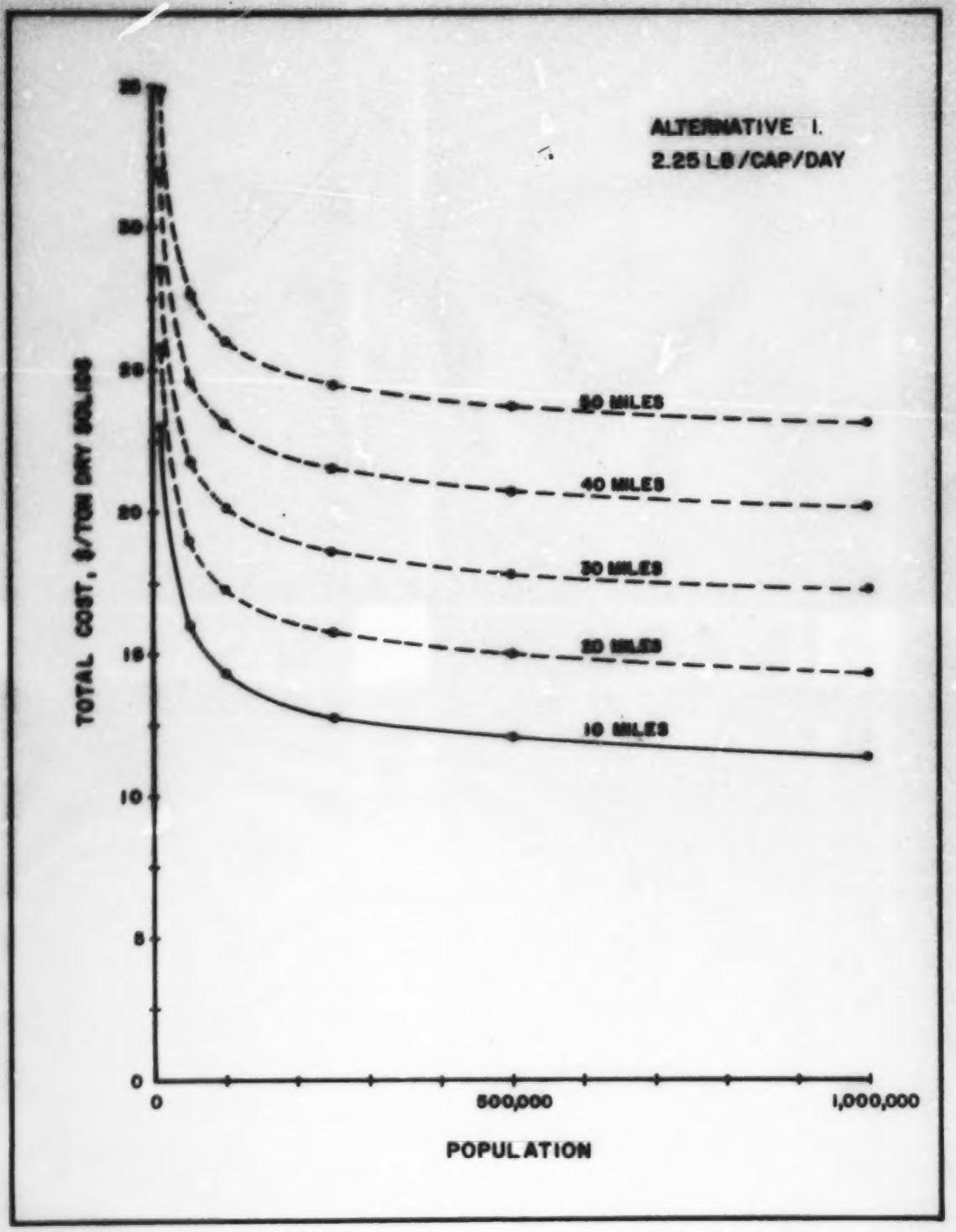

Figure 15: Total Cost of Sludge Handling (Alternative 1) as a Function of Population and Refuse Generation Rate of 2.25 lb/cap/day

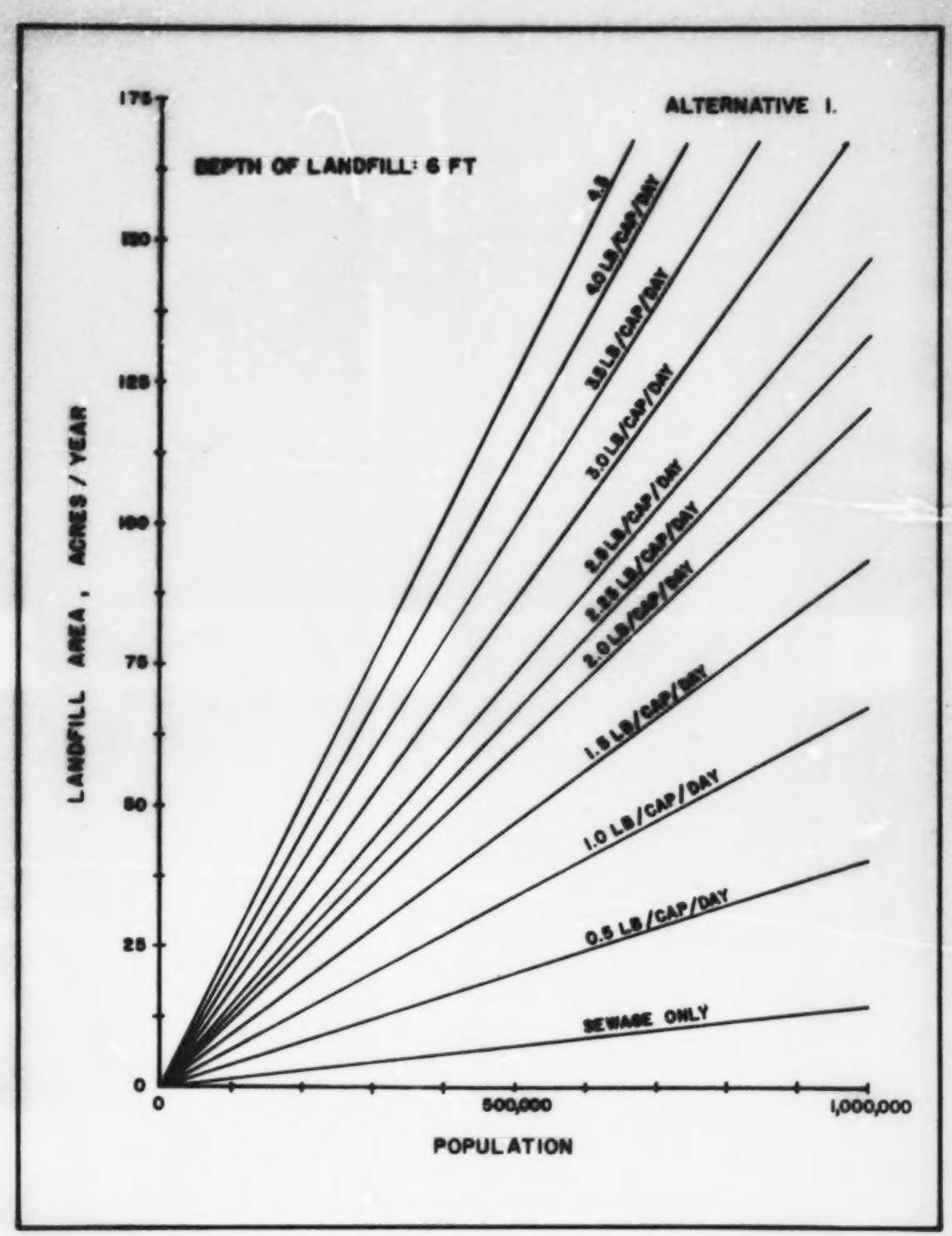

Figure 16: Landfill Area for the Undigested Sludge as a Function of Population and Refuse Generation Rate

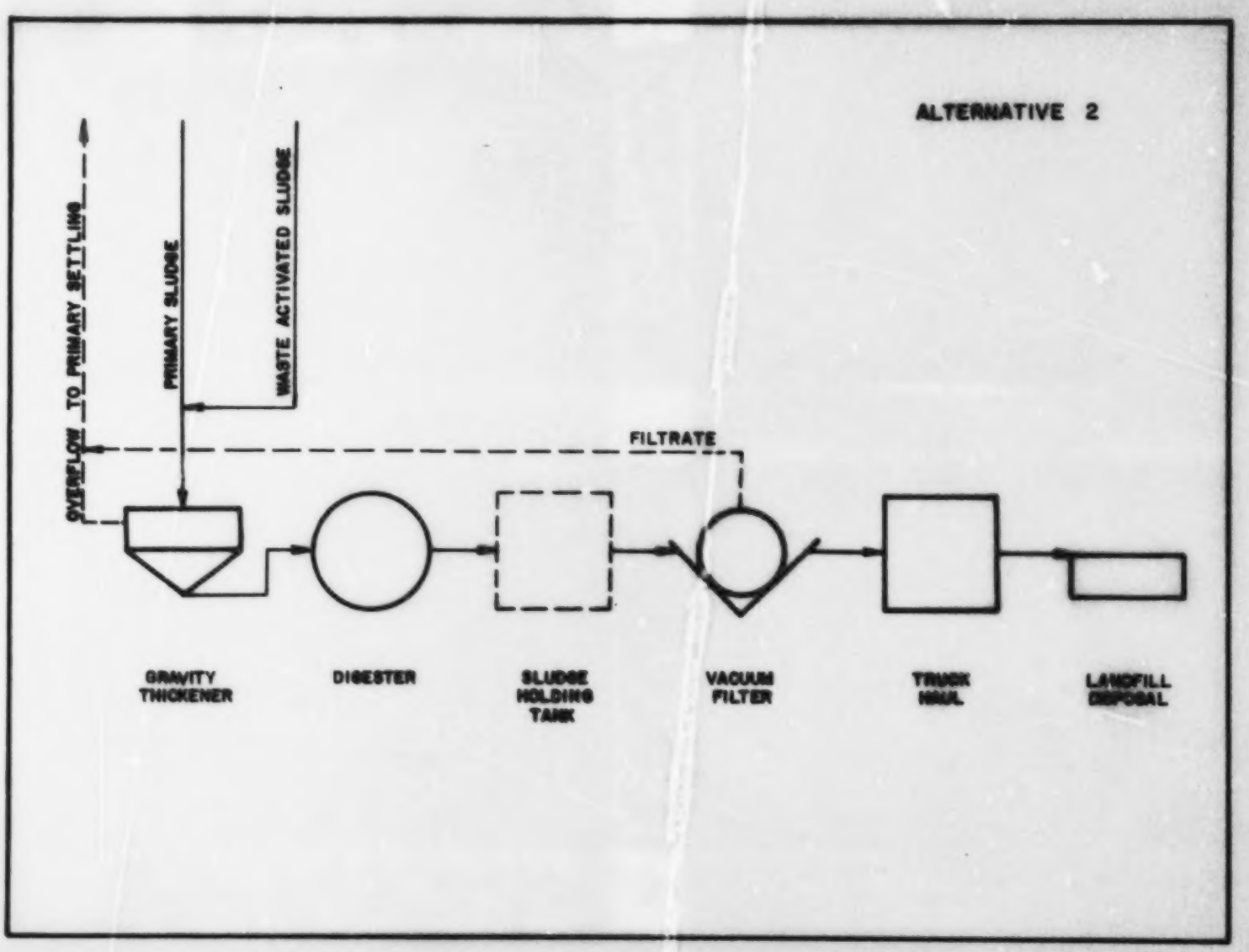

Figure 17: Sludge Handling, Alternative 2

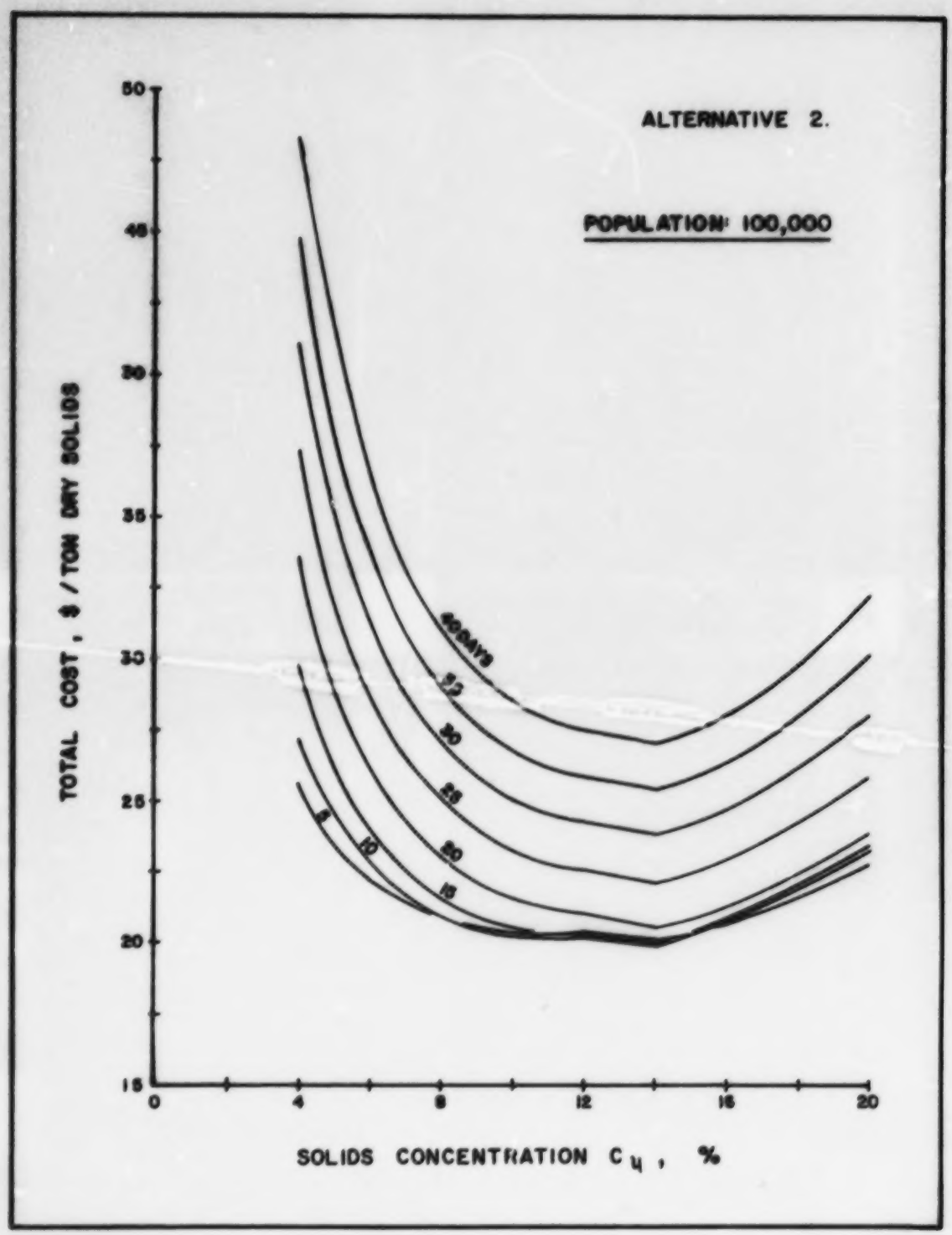

Figure 18: Total Cost of Sludge Handling (Alternative 2) as a Function of Concentration of Thickened Sludge and Detention Time of Digestion

time above 20 days, it should be remembered that the results of this figure depend quite substantially on the k value utilized in Equation [33].

Figure 19 shows the breakdown of costs for each unit operation for a 20-day detention time and a 100,000 population, again in terms of C_u. It is clear from this figure that the digester is the single most expensive unit operation in the combination, and that the digestion process has the greatest impact on the overall optimum.

Economies of Scale. Given the previously defined optimum conditions of 20-day digester residence time and C_u = 14% (which do not vary significantly with population size), Figure 20 shows the per ton cost as a function of population size. Also shown is the total cost after subtraction of the $5.88/ton ($6.48/kkg) benefit for digester gas. Figure 21 shows the per ton cost as a function of population, plotted for various refuse generation rates. As in the case of Alternative 1, the cost curve for sewage sludge alone lies considerably above that of ground refuse-sewage sludge mixtures.

Alternative 3

This alternative, the process configuration of which is shown on Figure 22, has replaced the truck haul and landfill disposal of Alternatives 1 and 2 by incineration. With the exception of the addition of the thickener, this alternative corresponds to that suggested by Metcalf & Eddy in their preliminary analyses.

Figure 23 shows the total cost of sludge handling as a function of C_u and population. In contrast to the previously examined alternatives, there is little dependence of total cost on C_u and no well defined optimum for the larger-sized facilities. Moreover, the cost of incineration dominates all other unit costs, as shown on Figure 24.

Finally, Figure 25 shows the dependence of cost on refuse generation rate and population size. Note that the difference between the cost of treating sewage sludge only and that for treating ground refuse is greater than that of the previously examined alternatives.

Alternative 4

In the final process configuration examined, a digester was added to process Alternative 3, as shown on Figure 26. The rationale for investigating incineration in conjunction with digestion was based on the premise that digestion would destroy a significant fraction of the sludge solids, thereby reducing the required capacity, and hence capital cost, of the incinerator. However, this decrease in incinerator capital cost is offset by an increase in operating cost, because the sludge cake after digestion will have a lower thermal value and hence

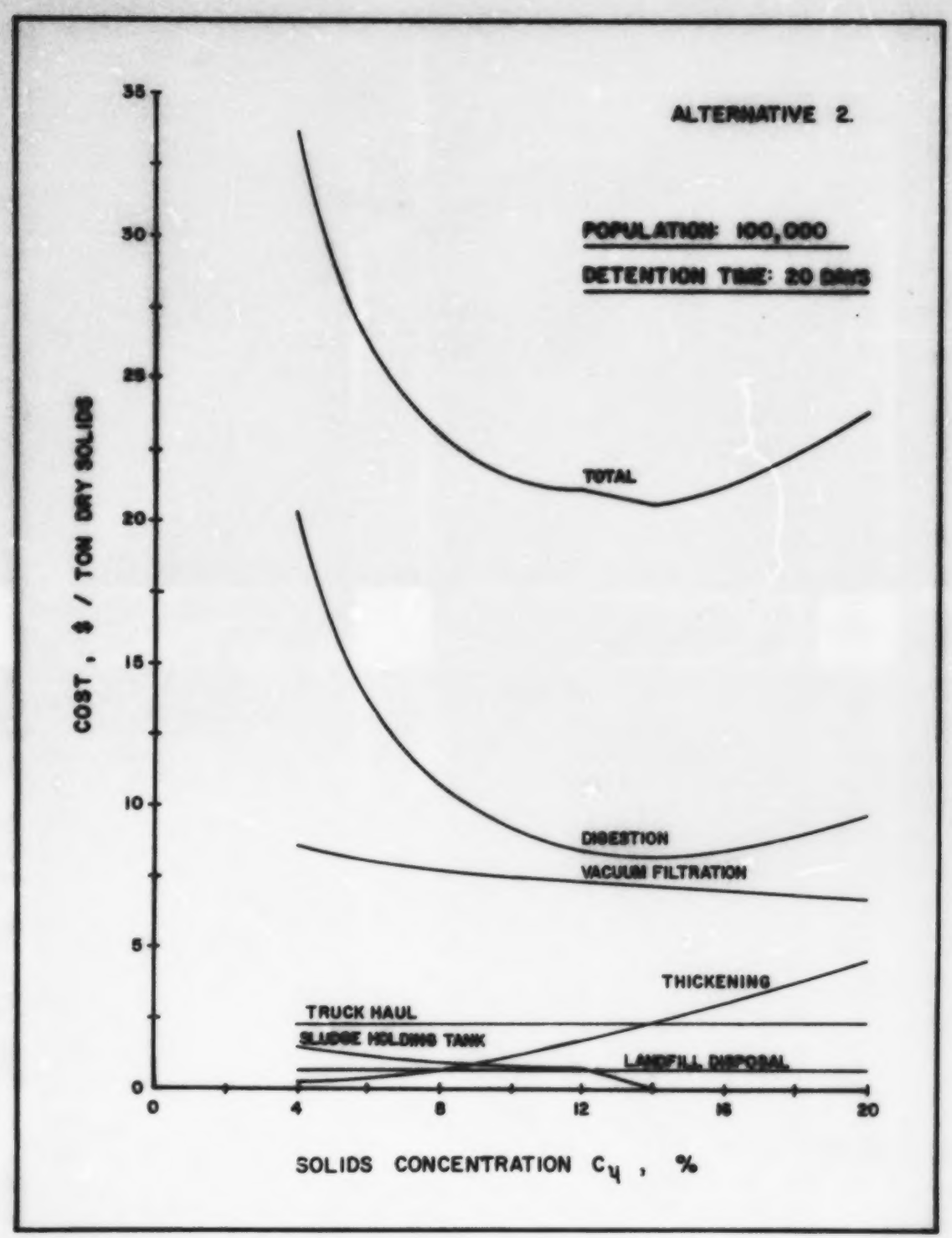

Figure 19: Cost of Particular Processes of Alternative 2 as a Function of Concentration of Thickened Sludge

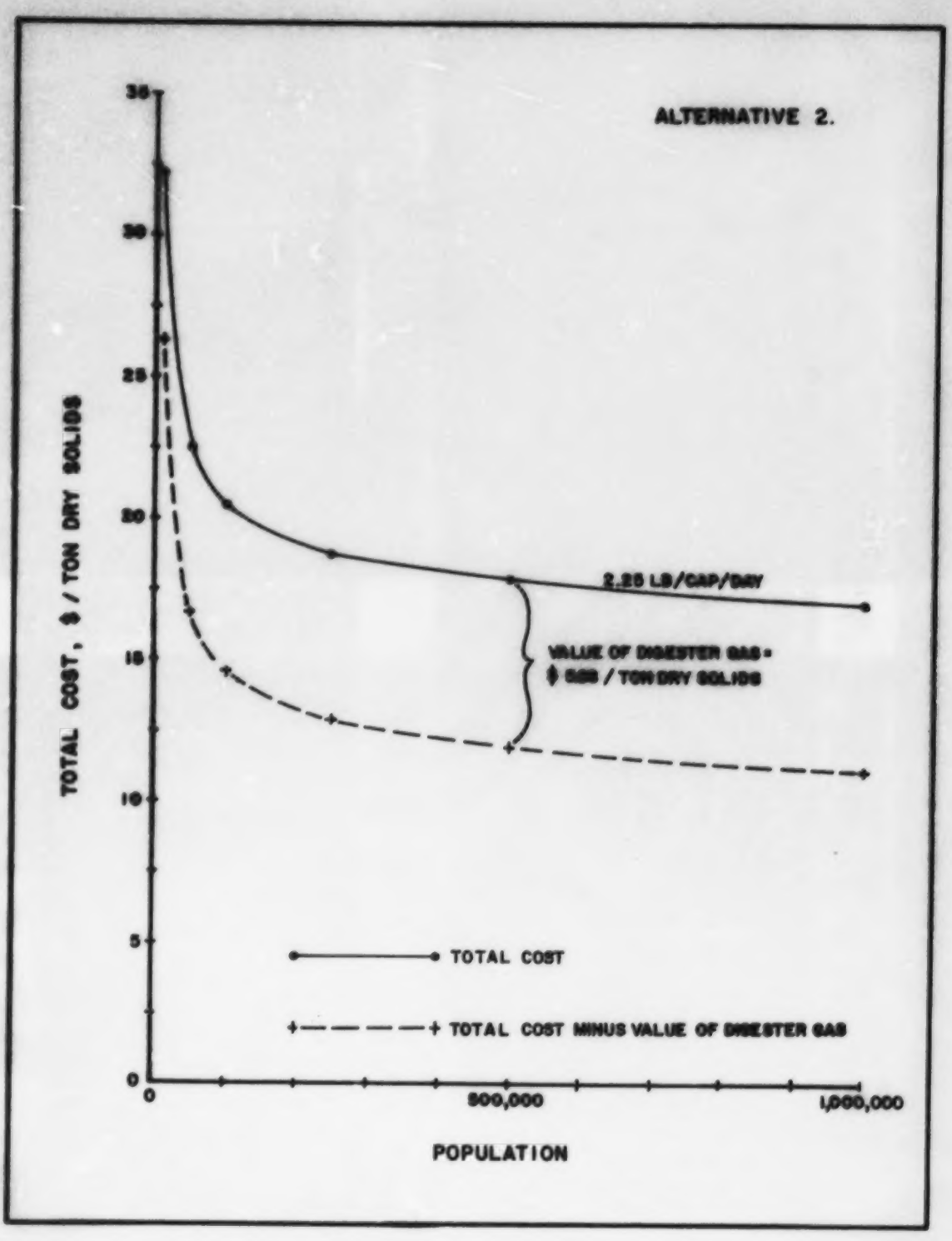

Figure 20: Total Cost of Sludge Handling (Alternative 2) as a Function of Population and for Refuse Generation Rate of 2.25 lb/cap/day

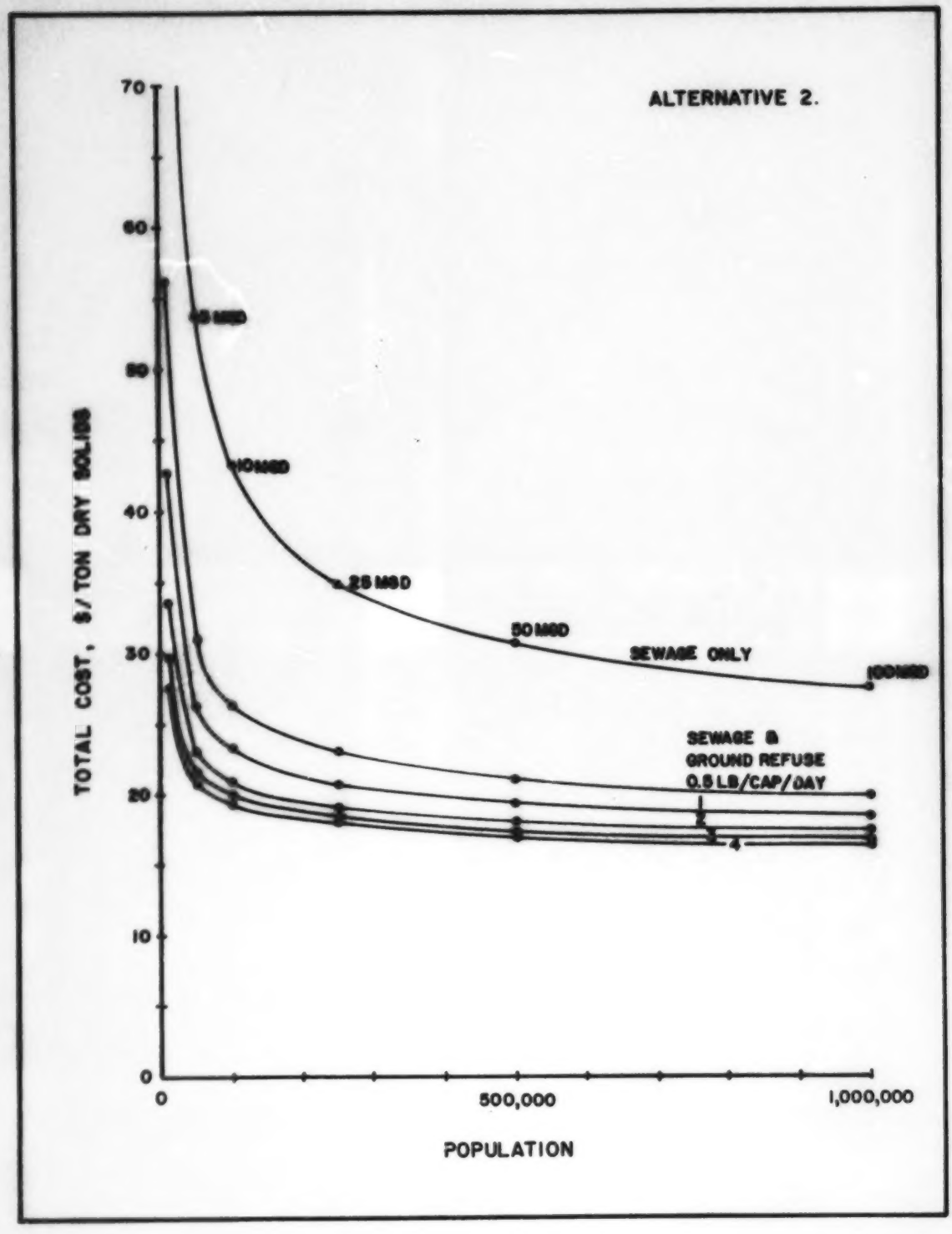

Figure 21: Total Cost of Sludge Handling (Alternative 2) as a Function of Population and Refuse Generation Rate

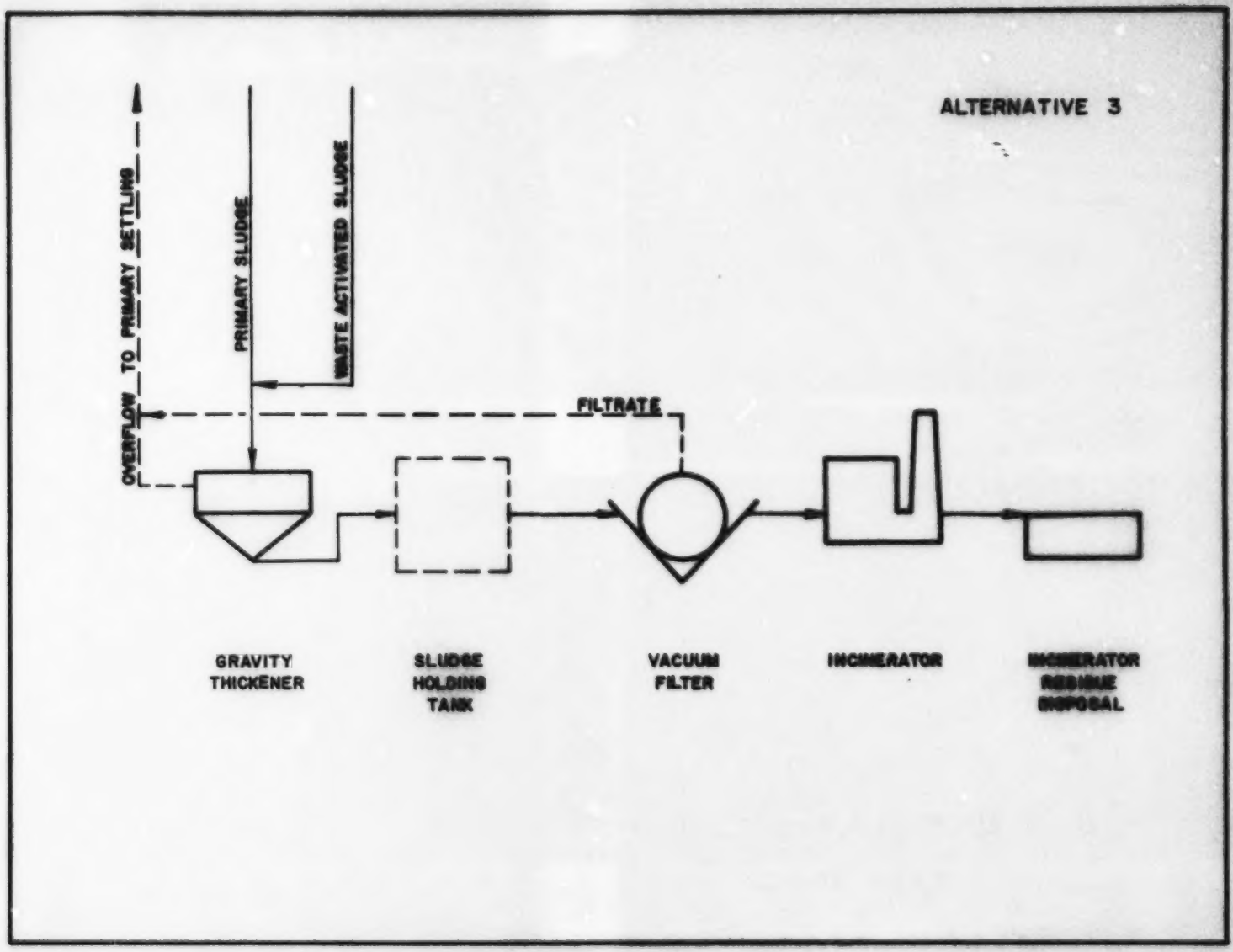

Figure 22: Sludge Handling, Alternative 3

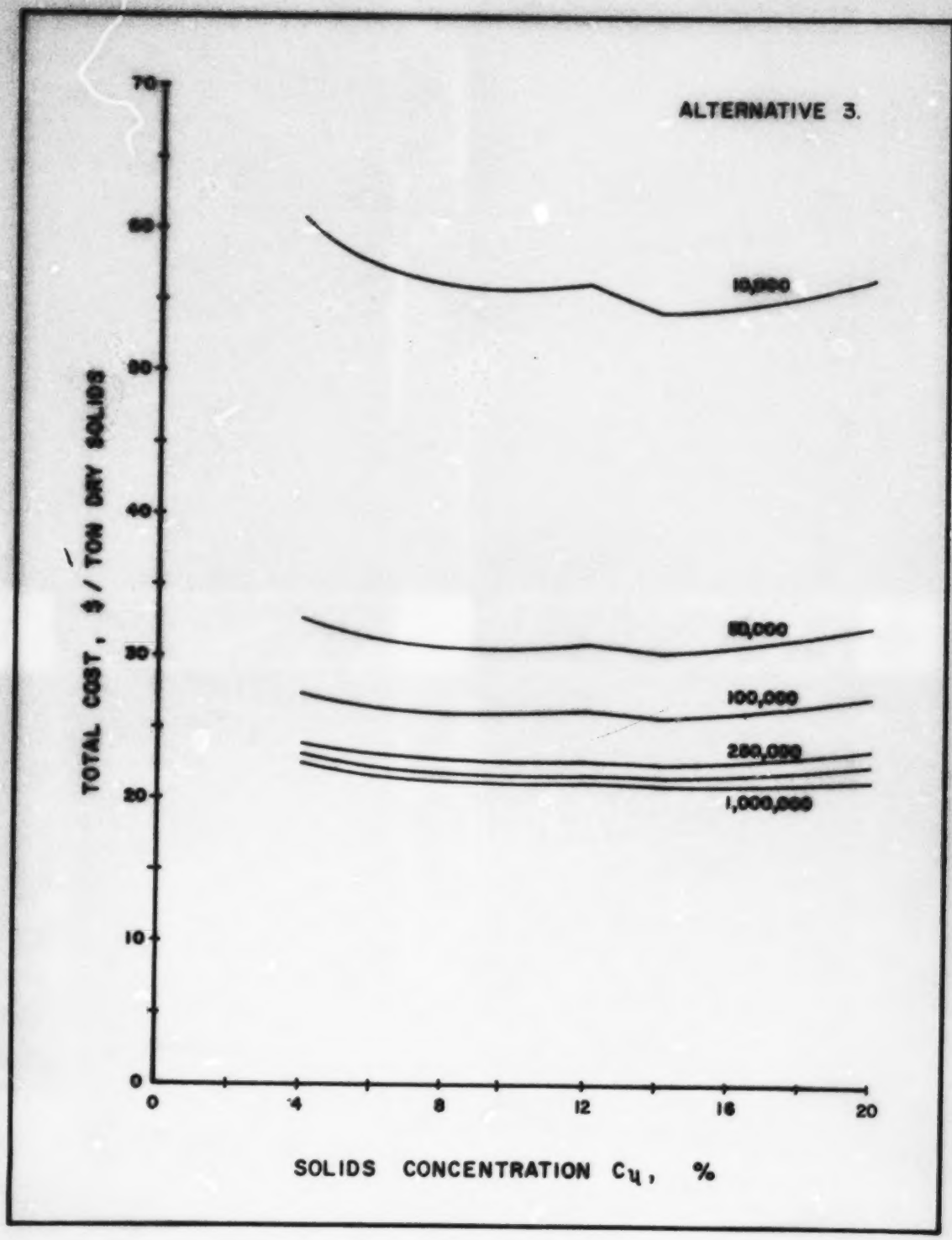

Figure 23: **Total Cost of Sludge Handling (Alternative 3) as a Function of Concentration of Thickened Sludge**

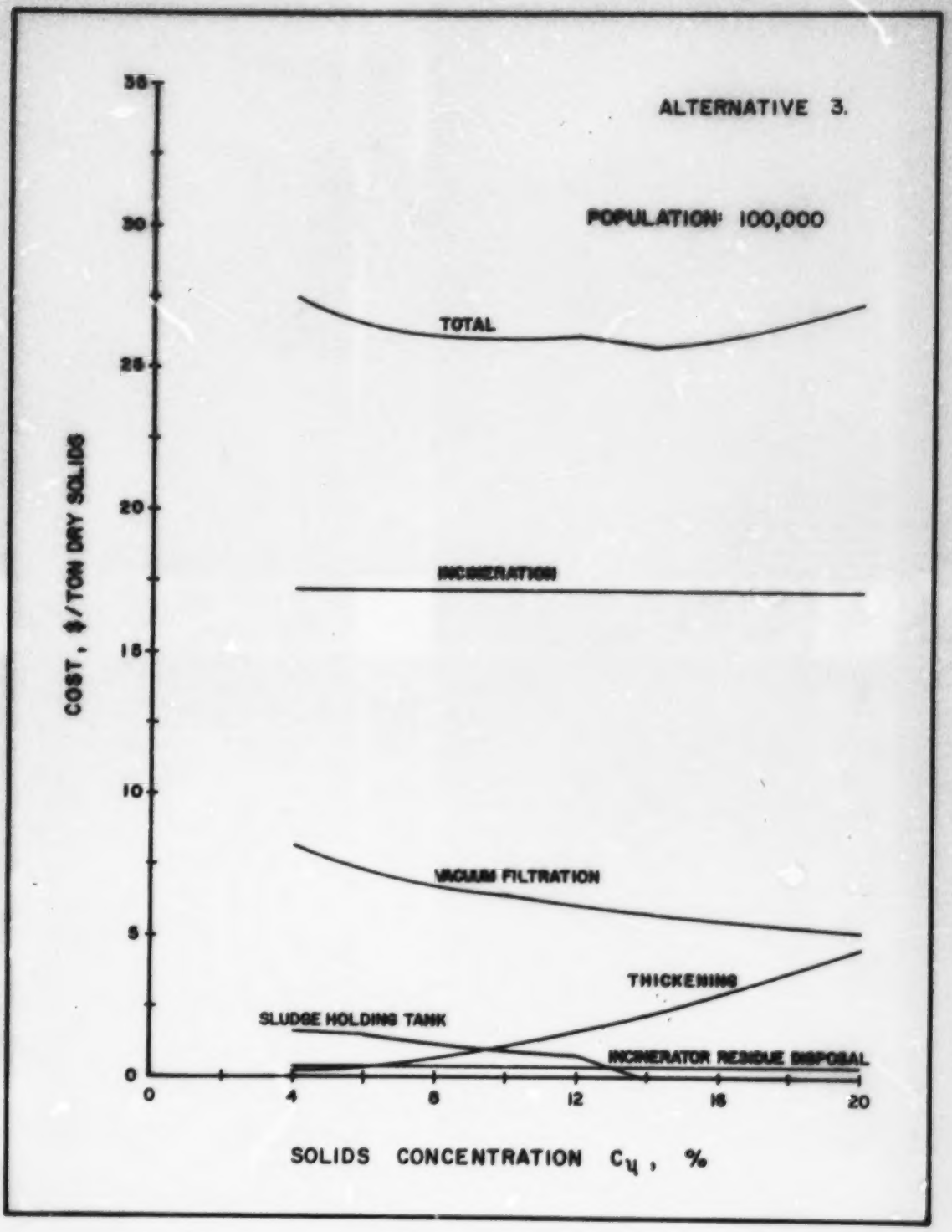

Figure 24: Cost of Particular Processes of Alternative 3 as a Function of Concentration of Thickened Sludge

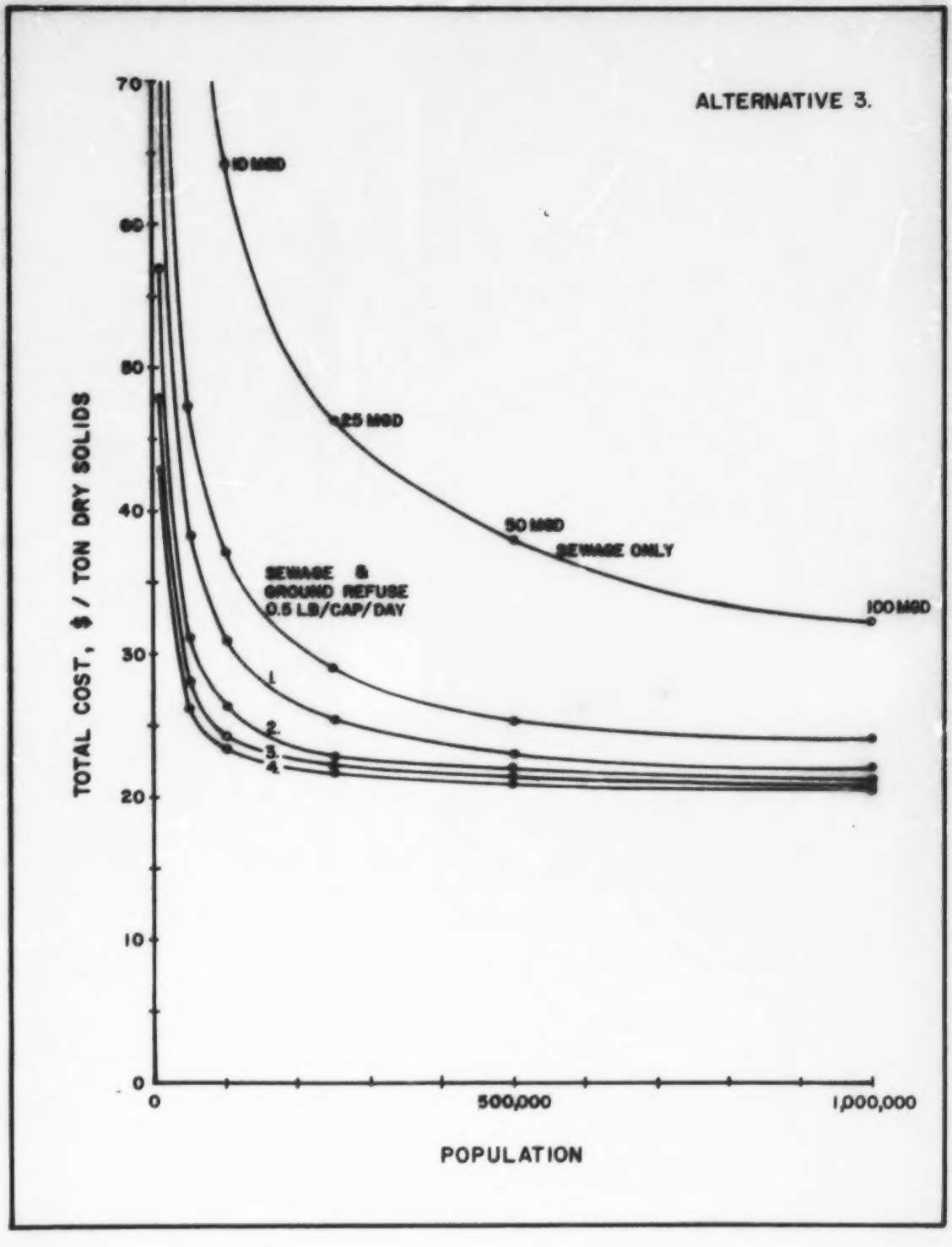

Figure 25: Total Cost of Sludge Handling (Alternative 3) as a Function of Population and Refuse Generation Rate

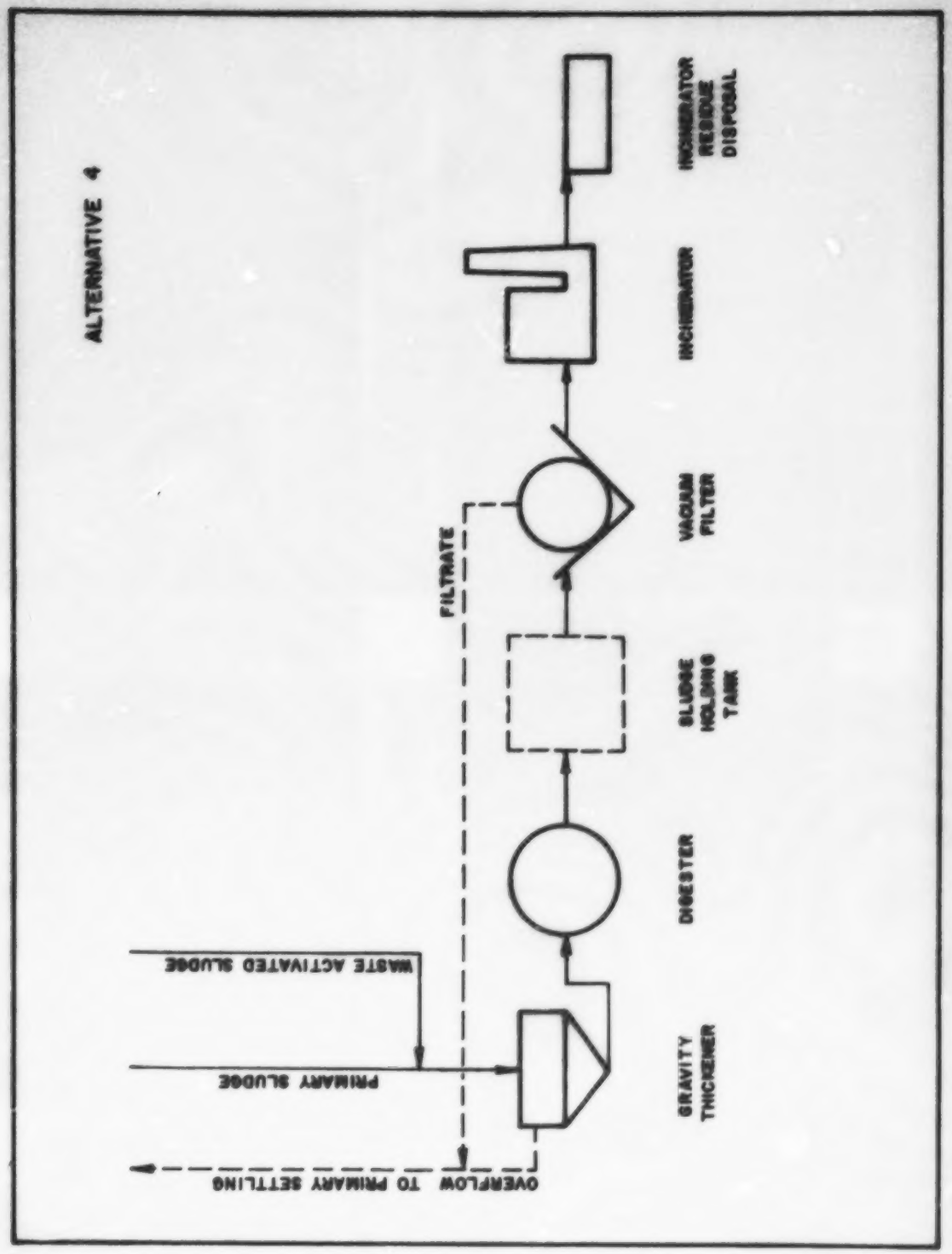

Figure 26: Sludge Handling, Alternative 4

additional supplementary fuel is needed. We have already established that the value of the digester gas (at $0.80/1000 cu ft) is about equal to the cost of building and operating a digester, and hence the feasibility of the digester-incinerator combination is determined by the trade-off between capital and operating cost of the incinerator. Alternatively, it might be reasoned that the digester gas itself be used as the supplementary fuel. Then the trade-off would be between the need for digester capacity as against reduction in incinerator capacity.

As in the case of Alternative 1, there is a pronounced optimum in total cost at a digester feed of C_u = 14%, as shown on Figure 27. Similarly, at optimum concentrations there is little sensitivity on digester detention time below 20 days; whereas higher detention times do carry heavy cost penalties. Figure 28 shows a breakdown of unit costs for a 20-day detention time and a 100,000 population; note that the optimum of total cost is again primarily dependent on the optimum of digestion. The dashed curves show the total cost and cost of digestion alone if the value of the digester gas is subtracted from the respective cost functions. Finally, Figure 29 shows the total cost as a function of population, both with and without the credit for digester gas.

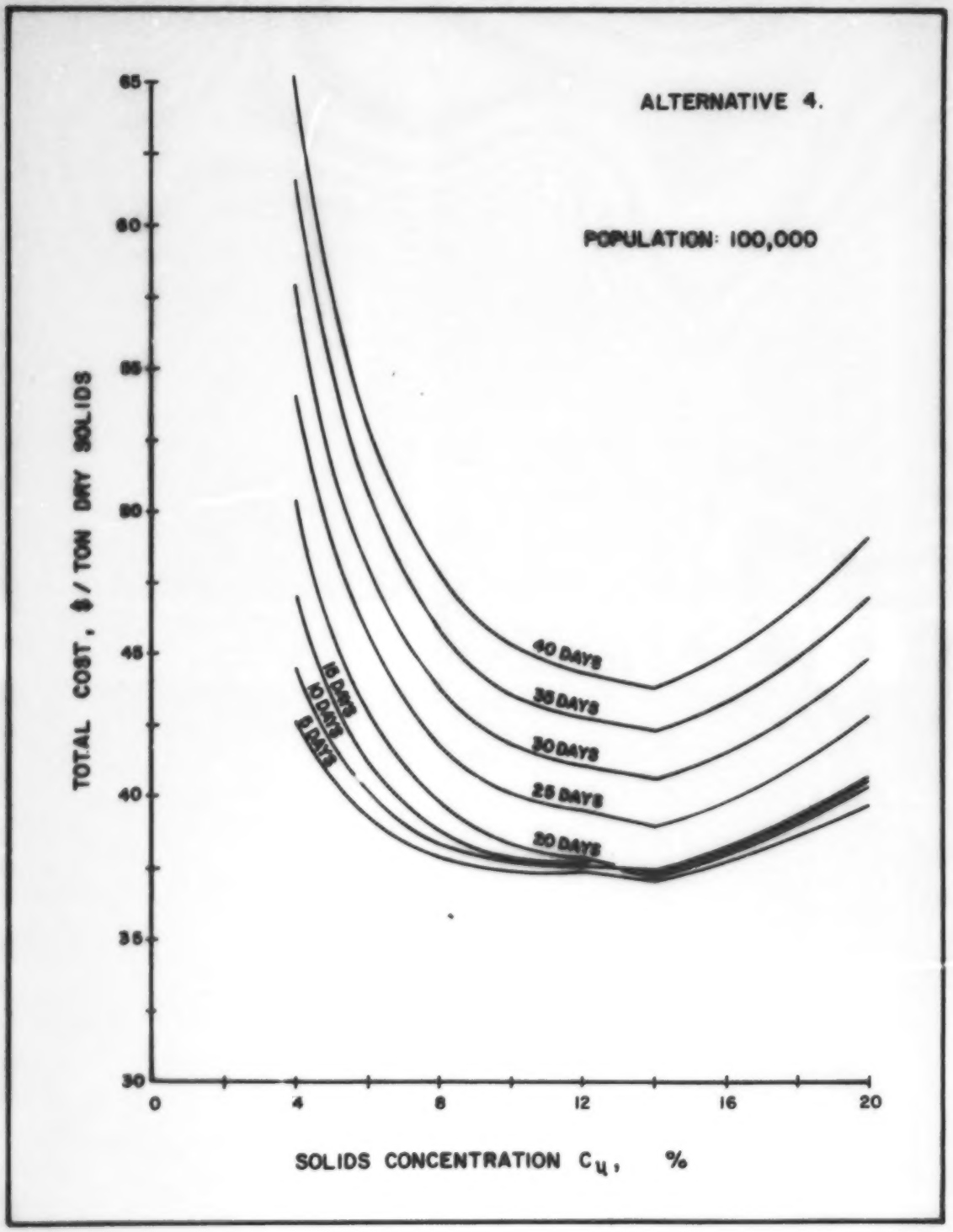

Figure 27: Total Cost of Sludge Handling (Alternative 4) as a Function of Concentration of Thickened Sludge and Detention Time of Digestion

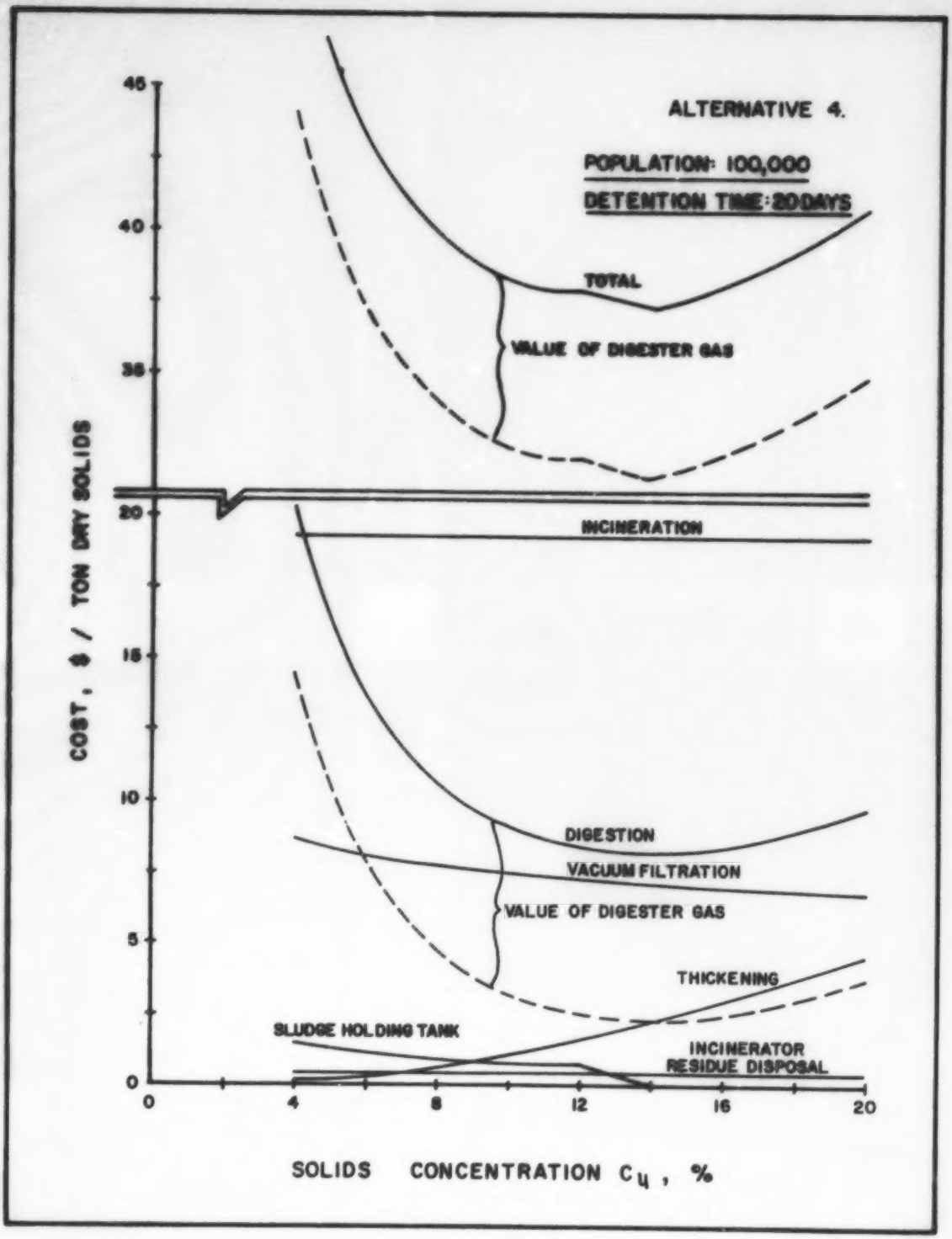

Figure 28: Cost of Particular Processes of Alternative 4 as a Function of Concentration of Thickened Sludge

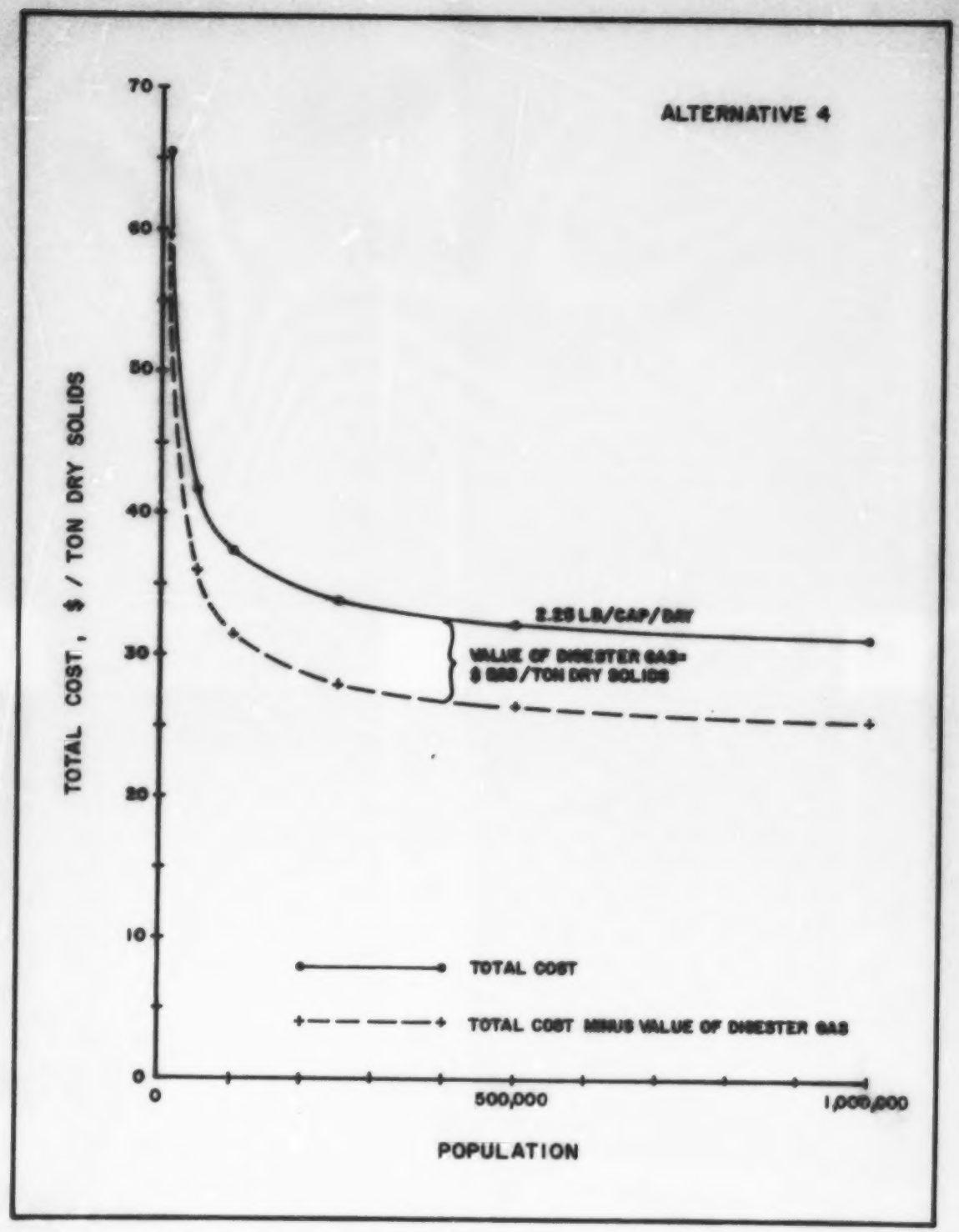

Figure 29: Total Cost of Sludge Handling (Alternative 4) as a Function of Population; for Refuse Generation Rate of 2.25 lb/cap/day

CHAPTER V

SUMMARY AND CONCLUSIONS

Sludge Quantity and Quality

The analysis of Chapter I showed a substantial increase in the quantity of primary sludge if ground refuse is added to sewage. In the case of an average raw refuse generation rate of 2.25 lb/cap/day (1.02 kg/cap/day), the addition of ground refuse to the sewage will result in about a fifteen fold increase in the quantity of primary sludge. On the other hand, the quantity of the sludge from secondary treatment will change only slightly. Therefore, the primary sludge will be the major determinant of sludge handling at a sewage treatment plant handling ground refuse. The sludge handling facilities of a sewage-refuse treatment plant for a community having an average raw refuse generation rate of 2.25 lb/cap/day would resemble those of the ordinary sewage treatment plant for an approximately nine times larger population.

Because of the very high ratio of primary sludge to other sludges (the ratio of primary to waste activated sludge is 12:1 for an average raw refuse generation rate) and because of strong scale economies, the handling of all sludges in a single stream is indicated. The quality of that mixture will be determined predominantly by the quality of primary sludge.

Sludge Handling and Disposal

Comparison of Alternative Process Configurations. The costs of the three feasible process configurations examined in Chapter IV are summarized on Figure 30. Alternative 1, involving thickening, vacuum filtration and land disposal, is the indicated choice, with a cost of between \$10-\$15 per ton (\$11.02-\$16.53 per kkg) of dry solids for facilities serving in excess of 100,000 population. If a digester is added (Alternative 2), total costs will be about \$5/ton (\$5.51/kkg) dry solids higher, an increase that is entirely offset by the value of the digester gas produced. Under the assumed conditions of a landfill at 10 miles (16 km) distance, incineration as a means of disposal (Alternative 3) is shown to be another \$4/ton (\$4.41/kkg) more expensive. Digestion together with incineration was dismissed as an economically infeasible alternative.

Tables 3, 4, and 5 summarize the costs of these three alternatives as a function of population size and per capita refuse generation rate, with an indication of the corresponding cost for a facility treating only sewage sludge. It is quite evident that the unit cost of handling sludge at a facility handling ground refuse is substantially lower than if only sewage sludge was handled. This is due to the economies of scale resulting from larger absolute quantities involved, and

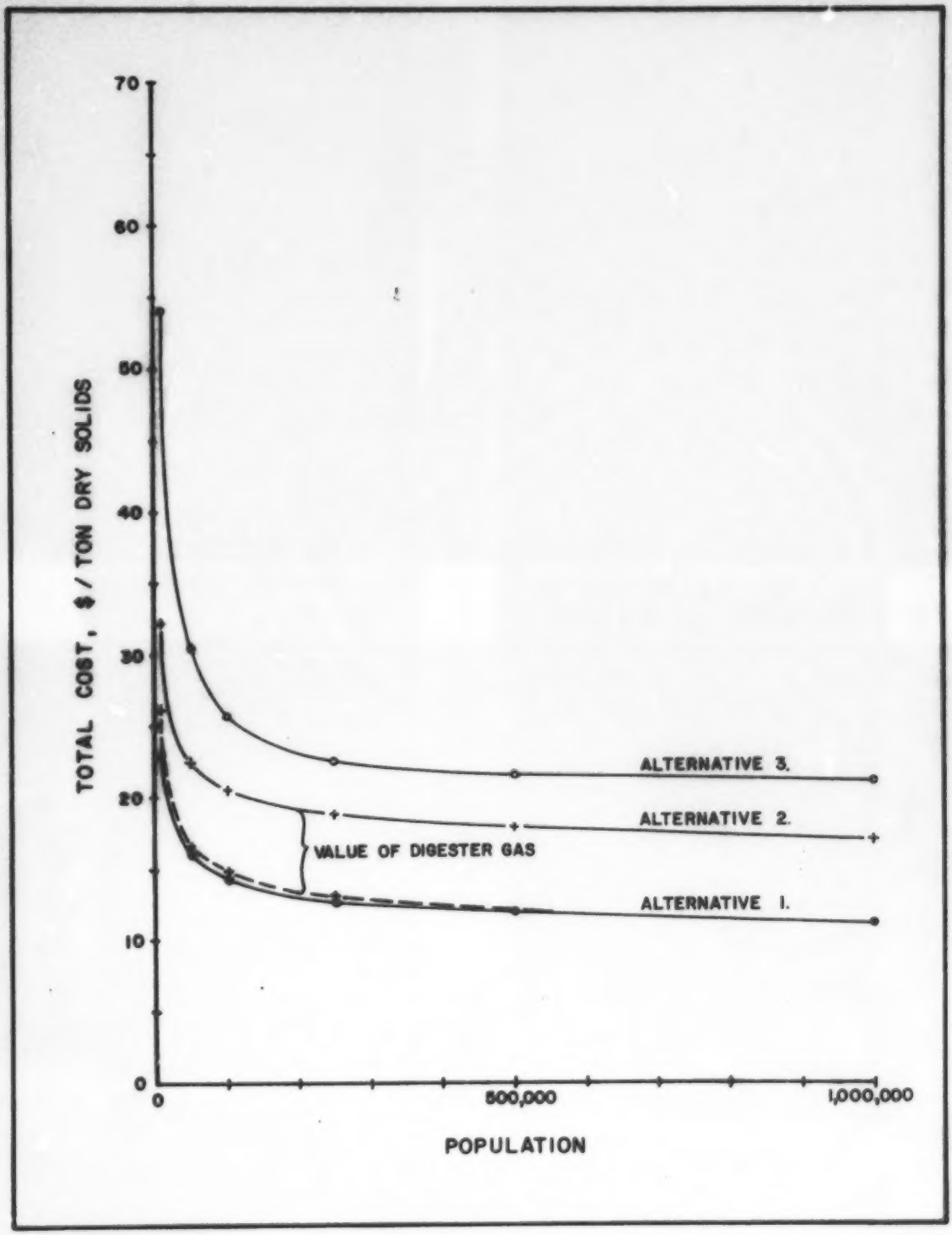

Figure 30: Total Cost of Sludge Handling (Alternative 1, 2 and 3) as a Function of Population; for Average Refuse Generation Rate of 2.25 lb/cap/day

TABLE 3: TOTAL COST OF SLUDGE HANDLING (ALTERNATIVE 1) IN $/TON DRY SOLIDS FOR VARIOUS POPULATIONS AND VARIOUS RAW REFUSE GENERATION RATES.

Raw Refuse Generation Rate lb/cap/day	POPULATION					
	10,000	50,000	100,000	250,000	500,000	1,000,000
0 (Sewage Sludge Only)	80.75	41.96	34.23	27.68	23.98	21.03
0.5	39.16	22.79	19.59	16.58	14,95	13.69
1.0	30.35	19.21	16.72	14.47	13.27	12.36
2.0	23.92	16.26	14.55	12,97	12.10	11.47
2.25	23.04	15.99	14.31	12.76	11.95	11.35
3.0	21.13	15.07	13.66	12.30	11.60	11.11
4.0	19.51	14.37	13.09	11.93	11.33	10.92

TABLE 4: TOTAL COST OF SLUDGE HANDLING (ALTERNATIVE 2) IN $/TON DRY SOLIDS FOR VARIOUS POPULATIONS AND VARIOUS RAW REFUSE GENERATION RATES.

Raw Refuse Generation Rate lb/cap/day	POPULATION					
	10,000	50,000	100,000	250,000	500,000	1,000,000
0 (Sewage Sludge only)	134.58	53.94	43.25	34.72	30.57	27.32
0.5	56.30	30.95	26.52	22.93	21.09	19.74
1.0	42.71	26.31	23.20	20.68	19.34	18.31
2.0	33.46	22.93	20.87	19.07	18.07	17.20
2.25	32.25	22.47	20.54	18.84	17.89	17.03
3.0	29.64	21.58	19.86	18.36	17.48	16.61
4.0	27.47	20.70	19.27	17.94	17.09	16.20

TABLE 5: TOTAL COST OF SLUDGE HANDLING (ALTERNATIVE 3) IN $/TON DRY SOLIDS FOR VARIOUS POPULATIONS AND VARIOUS RAW REFUSE GENERATION RATES

Raw Refuse Generation Rate lb/cap/day	POPULATION					
	10,000	50,000	100,000	250,000	500,000	1,000,000
0 (Sewage Sludge only)	265.74	87.67	64.15	46.28	37.96	32.36
0.5	107.61	44.47	37.14	28.94	25.30	24.04
1.0	77.88	38.29	30.99	25.24	22.94	22.05
2.0	56.89	31.27	26.35	22.75	21.89	21.26
2.25	54.08	30.30	25.72	22.44	21.64	21.04
3.0	48.01	28.17	24.37	22.56	21.45	20.77
4.0	42.92	26.37	23.29	21.80	21.20	20.64

the very different physical nature of the sludge to be dewatered and disposed.

Optimal Solids Concentrations. Our analyses show that in those cases where the total cost is sensitive to solids concentration, such as those process configurations involving digesters, an optimum appears to lie in the vicinity of 14 percent solids. If this appears high, as it doubtless does in comparison to solids concentrations encountered at existing treatment plants, one should be reminded of the drastically different nature of the sludge involved. A feed of such a high solids concentration is essential whenever digesters are used, as the cost of digester capacity would otherwise be prohibitive. Where digesters are not used, the decrease of vacuum filtration cost resulting from higher solids concentration is balanced by the increase in the cost required to thicken the sludge to the higher concentration, and no optimum solids concentration can be identified.

Digestion. Our calculations show that the cost of anaerobic digestion is somewhat higher than the resultant value of methane produced, and that the cost of process configurations using landfill for ultimate disposal is insensitive to whether or not digestion is included, given a methane value of $0.80 per 1000 cu ft ($28.50/100 cu.m). A lesser methane value would make the use of digesters unlikely, whereas an increased value, or consideration of the more intangible benefits of increasing energy supplies given the current energy shortages, such as benefits to the balance of payments, would tend to make digestion more attractive. All this, of course, is contingent on the assumption that anaerobic digestion is in fact feasible, an assumption that is yet to be convincingly demonstrated. As noted in a recent paper on management aspects of methane production from solid wastes,[51] reliability of supply will play a crucial role in successful marketing of the recovered energy. But skeptics who cite the traditional unreliability of sewage treatment plant digesters as a key argument against digesters might be reminded that sophisticated physical-chemical sludge treatment methods, such as the wet oxidation processes currently very much in favor, are surely at least as dependent on trained and experienced operator personnel as are digesters.

The constraints of this study have not allowed as detailed an investigation of the trade-offs in digestion as will be necessary if digestion were to be seriously considered in an actual implementation. In particular, the physical characteristics of the digesting sludge require identification if factors such as mixing cost are to be adequately analyzed. Other areas not fully explored include the impact of climate (which has a substantial impact on heating costs), the relationship between detention time and reliability, the impact of recycling the digester supernatant to the secondary treatment stages, and nutrient addition. A comprehensive study focused on a complete economic model of digesters would thus be recommended as a segment of further investigations into sludge handling.

Disposal Method. Of the two disposal methods examined by this study, incineration is shown to be preferable to direct landfill disposal only if the distance to the landfill exceeds 45 miles (72.4 km). The magnitude of this critical distance, of course, is dependent on many contributory factors, and would tend to increase as the cost of air pollution control equipment drives up the cost of incineration, and would tend to decrease with increased land or unit transportation costs. But, given the political realities as they presently exist, it is questionable whether a city that cannot find a landfill site within its own city limits or with an immediately adjacent community could ever use a more distant landfill, regardless of cost. Thus, all that can usefully be concluded in general terms is that both alternatives are technically feasible, and that their cost is of comparable magnitude. One of the objectives of the case study evaluation of the wet systems concept is to examine these alternatives in the context of specific location. Indeed, it would appear that the wet systems concept offers little significant advantage over conventional practice with respect to the ultimate disposal problem. And although advanced technologies such as pyrolysis would offer one solution, such technologies are not dependent on a wet collection method.

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